# Wrestling Sprawl to the Ground: Defining and Measuring an Elusive Concept

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## *Abstract*

The literature on urban sprawl confuses causes, consequences, and conditions. This article presents a conceptual definition of sprawl based on eight distinct dimensions of land use patterns: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity. Sprawl is defined as a condition of land use that is represented by low values on one or more of these dimensions.

Each dimension is operationally defined and tested in 13 urbanized areas. Results for six dimensions are reported for each area, and an initial comparison of the extent of sprawl in the 13 areas is provided. The test confirms the utility of the approach and suggests that a clearer conceptual and operational definition can facilitate research on the causes and consequences of sprawl.

**Keywords:** Land use/zoning; Urban environment

## A metaphor rich in ambiguity

Urban sprawl is one name for many conditions. It has been attached to *patterns* of residential and nonresidential land use, to the *process* of extending the reach of urbanized areas (UAs), to the *causes* of particular practices of land use, and to the *consequences* of those practices. Sprawl has been denounced on aesthetic, efficiency, equity, and environmental grounds and defended on choice, equality, and economic grounds. Sprawl has become the metaphor of choice for the shortcomings of the suburbs and the frustrations of central cities. It explains everything and nothing.

Much of the confusion about sprawl stems from the conflation of ideology, experience, and effects. A term so widely used cannot be easily dismissed as too vague for serious discussion. Many policy makers claim to know it when they see it and make important policy judgments based on what they see or think they see. As a first step toward developing policies to deal with the causes or consequences of sprawl, it would help both critics and apologists if agreement could be reached on what sprawl is and how to measure it empirically and compare its occurrence across a large number of urban areas.

## Sprawling literature: Lost in a semantic wilderness

Consistent with the findings of others (Burchell et al. 1998), our survey of the literature yielded no common definition of sprawl and relatively few attempts to operationally define it in a manner that would lead to useful comparisons of areas to determine which had experienced greater or less degrees of sprawl. There are two notable recent exceptions: First, Torrens and Alberti (2000) offer sophisticated indices for measuring multiple aspects of sprawl, such as density, scatter, leapfrogging, interspersion, and accessibility, but provide no empirical prototypes. Second, Malpezzi (1999) has undertaken an ambitious effort to develop some precise definitions of several dimensions of sprawl such as density and lack of continuity. Moreover, he has quantified them for a sample of metropolitan areas and related them statistically to determinants of sprawl such as the length of average daily commutes.

Our analysis of the social science and planning literature suggests that definitions of sprawl can be grouped into six general categories:

1.  Sprawl is defined by an example, which is seen to embody the characteristics of sprawl, such as Los Angeles.

2.  Sprawl is used as an aesthetic judgment about a general urban development pattern.

3.  Sprawl is a cause of an externality, such as high dependence on the automobile, isolation of the poor in the inner city, the spatial mismatch between jobs and housing, or loss of environmental qualities.

4.  Sprawl is the consequence or effect of some independent variable, such as fragmented local government, poor planning, or exclusionary zoning.

5.  Sprawl is defined as one or more existing patterns of development. Those most frequently mentioned are low density, leapfrogging, distance to central facilities, dispersion of employment and residential development, and continuous strip development.

6. Sprawl is defined as a process of development that occurs over some period of time as an urban area expands.

## Definition by example

In both the popular and scholarly literature, sprawl is frequently defined by one or more examples of scattered or low-density patterns of urban development. Los Angeles is often given a place of honor in exemplary definitions. Robert Geddes (1997) asserted, "Its key words are *fragmented*, *incomplete*, *ad hoc*, *uncentered*" (3). Unfortunately, while it is big and spread over a large area, Los Angeles is more densely settled than most large areas in the United States. Atlanta has come to replace it as an example of sprawl, but with the possible exception of Portland, OR, any area is a potential nominee. The flexibility of definition by example makes it possible to include all sorts of development patterns, from planned communities with clustered housing and mixed uses to exurban rural estates. A Wells Fargo Bank report, *Preserving the American Dream*, concluded that sprawl "receives blame for seemingly every bad aspect of contemporary urban life" (quoted in Myers and Kitsuse 1999, 6).

## Aesthetic definition

Ad hoc examples at least imply and often express an aesthetic judgment: Sprawl is ugly development. In *The Language of Cities* (1971) Charles Abrams defined sprawl as follows: "The awkward spreading out of limbs of either a man or a community. The first is a product of bad manners, the second of bad planning" (293–94). Even so careful a land economist as Marion Clawson (1962) could not resist judgmental adjectives and adverbs in his definition: "[the] rapid spread of suburbs across the previously rural landscape, tendency to discontinuity, large closely settled areas intermingled haphazardly with unused areas" (94).

## The cause of an unwanted externality

Traffic congestion (Black 1996; Downs 1999; Vermont Forum on Sprawl 1999), environmental contamination (Sierra Club 1998), income and racial segregation of neighborhoods (Downs 1998), the mismatch between jobs and housing (Orfield 1997), local fiscal disparities (Burchell et al. 1998), conversion of farmland to urban uses (U.S. General Accounting Office [GAO] 1999), and civic alienation (Popenoe 1979), among other maladies of contemporary urban life, have been attributed to sprawl. Here the definitions segue from judgments about the appearance of sprawl to assertions of causal links between sprawling land use patterns

and environmental, social, and economic costs. But these definitions basically describe what sprawl does (or is supposed to do) rather than what it is.

## A consequence

Sprawl is also frequently defined as the consequence of something else. Downs (1998), among others (Black 1996; Burchell et al. 1998; Moskowitz and Lindbloom 1993; Orfield 1997), argues that sprawl occurs as a consequence of the fragmentation of control over land use in metropolitan areas. It is unclear whether sprawl is an intentional, necessary, or inadvertent consequence of fragmented governance of growth. In light of development patterns in areas with unified governments, such as Houston and Lexington, KY, it seems a doubtful proposition. In any event, understanding the policies that induce specific development patterns could lead to their correction if there were a clearer specification of what those patterns are.

## Selected patterns of land development

Altshuler and Gomez-Ibanez (1993) edge toward a clearer definition of sprawl by identifying the types of development patterns associated with it:

> Continuous low density residential development on the metropolitan fringe, ribbon low density development along major suburban highways, and development that leapfrogs past undeveloped land to leave a patchwork of developed and undeveloped tracts. (67)

The inconsistency of continuous and leapfrog development aside, this definition at least characterizes land use conditions, and it is conceivable that continuous development, ribbon development along corridors, and leapfrog development are different forms of sprawl (Harvey and Clark 1965). Other development patterns frequently characterized as sprawl include low density (Lockwood 1999), random (GAO 1999), large-lot single-family residential (Popenoe 1979), radial discontinuity (Mills 1980), single land use or physical separation of land uses (Burchell et al. 1998; Cervero 1991), widespread commercial development (Downs 1998), strip commercial (Black 1996; Burchell et al. 1998), and non-compact (Gordon and Richardson 1997).

## A process of development

Finally, some commentators (Ewing 1997; Harvey and Clark 1965) suggest that sprawl represents a stage in the development process rather

than a static condition. This definition suggests that some parts of an urban area may pass through a sprawl stage before eventually thickening and diversifying so they can no longer be characterized as sprawl, at least by those authors. When used to signify a stage or process of development, sprawl is a verb, rather than a noun connoting a condition. But little is gained by changing the part of speech, for there is little in the literature to indicate when sprawl metamorphoses into nonsprawl. It does, however, suggest that sprawl may represent some range on a development pattern continuum.

These descriptions of sprawl leave one grasping for something more solid. How far does the development frog have to leap and how light and broad must its footprint be for sprawl to be present? When do land uses thin sufficiently from being compact, centered, or concentrated before they degrade into sprawl? An empirical definition is needed if the discussion is to move from polemics to a common understanding and useful analysis of urban form. Once that is achieved, it should be possible to conduct a better-informed discussion of the forces and factors that cause certain patterns of development and to address the consequences that flow from certain urban forms for different population groups, such as a region's poor.

Conceptually, a thing cannot simultaneously be what it is and what causes it or what it causes. If sprawl is to be a useful concept for describing something important that occurs in urban areas, it must first be reduced to some objective conditions or traits. Some of the characterizations drawn from the literature are too impressionistic for empirical measurement. Others identify conditions, dimensions, or attributes of sprawl that can be operationally defined, among them discontinuous, widespread, or random development; low-density residential or nonresidential development; continuous low-density or strip development; spatially segregated land uses; and dispersed employment centers.

## A conceptual definition

As a noun, sprawl implies a condition characterizing an urban area, or part of it, at a particular time. If sprawl is to be measured as a condition of land use, it must be distinguished from other conditions that may well be related to it. On the basis of the descriptions of conditions characterizing it in the literature and amplified by observation and experience, the following conceptual definition is suggested:

> Sprawl (n.) is a pattern of land use in a UA that exhibits low levels of some combination of eight distinct dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity.

This definition suggests the possibility that there can be different types of sprawl, consisting of different combinations of these dimensions.[1] It also suggests the possibility of defining sprawl as a *process* of development by looking at changes in patterns of land use over time, particularly at the periphery.

Emphasizing the pattern of land use distinguishes the condition from its causes or effects. The pattern of land use refers to the arrangement of the built environment for residential and employment activities. Other uses, such as passive or active open space, agriculture, and public facilities and networks, will affect that pattern along some of its dimensions.

The UA is a more appropriate unit of analysis than the metropolitan area (MA), which is composed of contiguous counties, some of which may contain large outlying rural areas with population densities far below the minimum UA threshold of 1,000 people per square mile. Including such rural areas can result in exaggeration of some dimensions of sprawl, such as density. Using the census-defined UA alone, however, may exclude semirural development at the urban fringe that some consider the epitome of sprawl. Whatever its limitations, the UA is a well-established construct that captures settlements averaging as few as 2.4 units per acre and the vast majority of all development of the MA. It may ultimately be useful to add to the UA subdivisions that are integrally associated with it, as distinct from established rural homesites and outlying communities located in metropolitan counties. Using the UA alone, however, should provide a reasonable test of the ability of the eight dimensions to characterize the extent of sprawl within it. And if they can, they can also be applied to a carefully delineated larger area.

Despite its disagreements and contradictions, the literature agrees that all development is not sprawl; simply because a UA is larger does not mean that it is more sprawled. Moreover, all sprawl does not have the same characteristics or dimensions. Excluding terms that cannot be easily quantified, such as ugly or excessive, there appear to be several objective dimensions of land use, that, if present at low levels in a UA, can fairly be called sprawl. Therefore, if each dimension of land use pattern is placed on a continuum, the lower the level, the greater the extent of sprawl on that dimension. It would seem fair to characterize UAs with development patterns that score low on all dimensions as experiencing more sprawl than others. Further, the dimensions may be present in different degrees and combinations across many urban areas, making it possible to distinguish different types of sprawl.

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[1] In our conceptualization that sprawl is a multidimensional phenomenon, we are consistent with the work of Malpezzi (1999) and Torrens and Alberti (2000).

## Research strategy

This article reports the first two steps in a long-range research strategy. The first step, reported in the next section, identifies and develops conceptual and operational definitions of eight dimensions of sprawl (used as a noun). Each dimension consists of a continuum with low values representing more sprawl-like features. The study has not attempted to develop measures for sprawl as a process, although that is a worthy subject for further inquiry. In any event, measuring the respective dimensions of development patterns for an urban area at different times will reveal the process (or progress) of sprawl.

The second step tests the operational definitions by applying them to 13 large UAs from different regions, with different economic structures and demographic composition, to determine whether they make intuitive sense.

Future research contemplates making any necessary adjustments to the description or measurement of each dimension and applying the approach to the 100 largest UAs in the United States and ranking them on each of the eight dimensions, as well as any distinctive factors that emerge from the analysis. Techniques such as factor analysis can be used to determine whether distinct patterns or combinations of low values on these dimensions can be identified as different types of sprawl variables that will enable serious research on sprawl. The resulting variables could be used in models either as independent variables (What is the effect of different dimensions or types of sprawl on *X*?) or dependent variables (What causes particular dimensions or types of sprawl?).

## Eight dimensions of sprawl

We now offer eight conceptually distinct, objective dimensions of land use that if present at low values and in some combination, characterize sprawl.

### *Density*

Density is the average number of residential units per square mile of developable land in a UA.

Density is the most widely used indicator of sprawl (Black 1996; Burchell and Listokin 1991; Burchell et al. 1998; GAO 1999; Gordon and Richardson 1997; Lockwood 1999; Malpezzi 1999; Moskowitz and Lindbloom 1993; Orfield 1997; Popenoe 1979; Sierra Club 1998; Torrens and Alberti 2000). It is usually expressed simply, as the ratio of the total pop-

ulation of a metropolitan area to its total land area. However, residential units are a better unit for measuring sprawl as a physical condition of land use. And developable land—land that has no natural features, public uses, or regulatory barriers to its development at urban densities—is a better denominator for calculating density than total land area. It is also a more useful area for measuring all the other dimensions of land use patterns. Using developable land as a measure makes it possible to eliminate physical features and other constraints, such as public open space, that interrupt or preclude development, whether areas are assessed alone or compared.

Residential density is likely to be a more useful indicator than nonresidential development. First, that is the way the term is generally understood and used in the literature. Second, nonresidential uses are more likely than residential uses to be "lumpy" due to agglomeration economies and regulations that limit such development to fewer locations. Thus, their average density is a less reliable indicator of their pattern of distribution. And unlike the case of housing units, which bear a close relationship to population, the relationship between the number of business establishments and employees varies widely. The average employment per square mile might be a slightly more significant element of the density dimension, although it fluctuates with business cycles. Because we are examining sprawl as a condition of land use, and firms and employees are both far more likely to be clustered than residences, it may be more appropriate to examine them in another dimension.
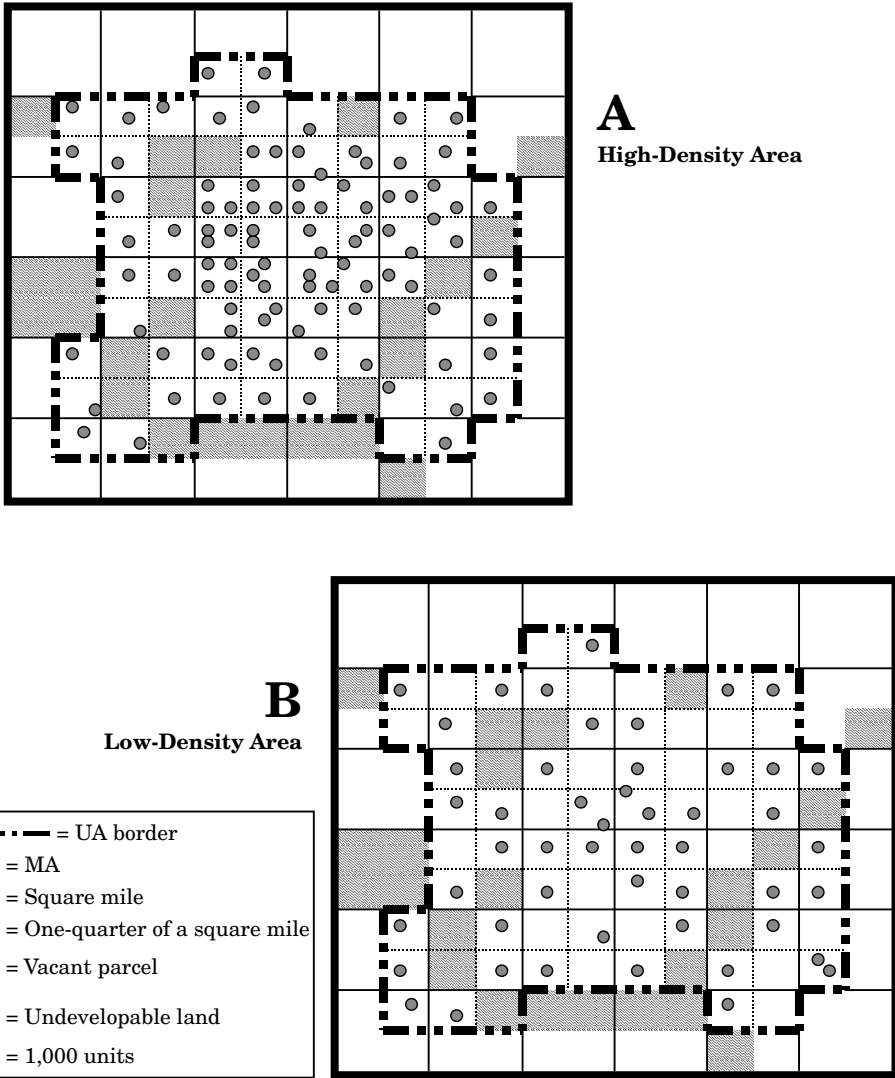
Figure 1 illustrates the density dimension. With the same gross land area, A has a greater number of residential units and thus higher density than B.

## Continuity

Continuity is the degree to which developable land has been built upon at urban densities in an unbroken fashion.

The second most cited dimension of development is continuity (Ewing 1997; Harvey and Clark 1965). Continuous development may occur at any level of density, although the steady outward march of low-density development in concentric rings from the urban center or core is commonly characterized as sprawl (Altshuler and Gomez-Ibanez 1993; American Society of Civil Engineers 1999; GAO 1999; Harvey and Clark 1965; Lockwood 1999). So is continuous "'ribbon' low-density development along major suburban highways" (Altshuler and Gomez-Ibanez 1993, 67; see also Ewing 1997 and Harvey and Clark 1965). Some commentators identify "discontinuity" as one of the significant attributes of sprawl (Clawson 1962), citing development that "leap-frogs past undeveloped land to leave a patchwork of developed and undeveloped tracts"

*Figure 1.* **Density: The Average Number of Residential Units
per Square Mile of Developable Land in a UA**



**A**

**High-Density Area**

**B**

**Low-Density Area**

- · – · · – · = UA border
- = MA
- —— = Square mile
- ---- = One-quarter of a square mile
- ☐ = Vacant parcel
- ▨ = Undevelopable land
- ◉ = 1,000 units

(Altshuler and Gomez-Ibanez 1993, 67; see also Burchell and Listokin 1991; Burchell et al. 1998; Ewing 1997; Gordon and Richardson 1997; Harvey and Clark 1965; Mieszkowski and Smith 1991; Mills 1980).

Following these definitions, sprawl can be continuous in some places and discontinuous in others. Discontinuous development could be characterized as sprawl in some cases but as something else in others. Thus, the development of planned urban centers with moderate to high densities, separated along a transportation corridor by greenbelts or other open spaces, might not be characterized by some commentators as sprawl,

although development of low-density subdivisions or commercial centers or industrial/office parks that have passed over developable land might be so characterized. The literature, however, rarely distinguishes between the smooth and lumpy spread of development across the landscape. This is particularly true when density is measured solely by the ratio of population to land area. More sophisticated approaches have used alternative indicators of density gradients to capture both the density and noncompact aspects of sprawl, such as the density of the census tract containing the 10th percentile of the MA population (Malpezzi 1999).

As defined here, the continuity dimension is concerned with density only as a means of determining whether a tract of developable land contains enough housing units or employment to consider it part of a continuous pattern or skipped over. Thus, the continuity dimension indicates only the extent of leapfrog development. UAs with discontinuous development patterns will have low scores on this dimension. Bodies of water; protected wetlands, forests, parks, slopes, or soils; and freeways, interchanges, or other public reservations and facilities are not considered interruptions of continuous development patterns.

Figure 2 illustrates the application of the continuity dimension to two urban areas containing the same amount of development. A has a high level of continuity, but B has less and exhibits a leapfrog pattern.
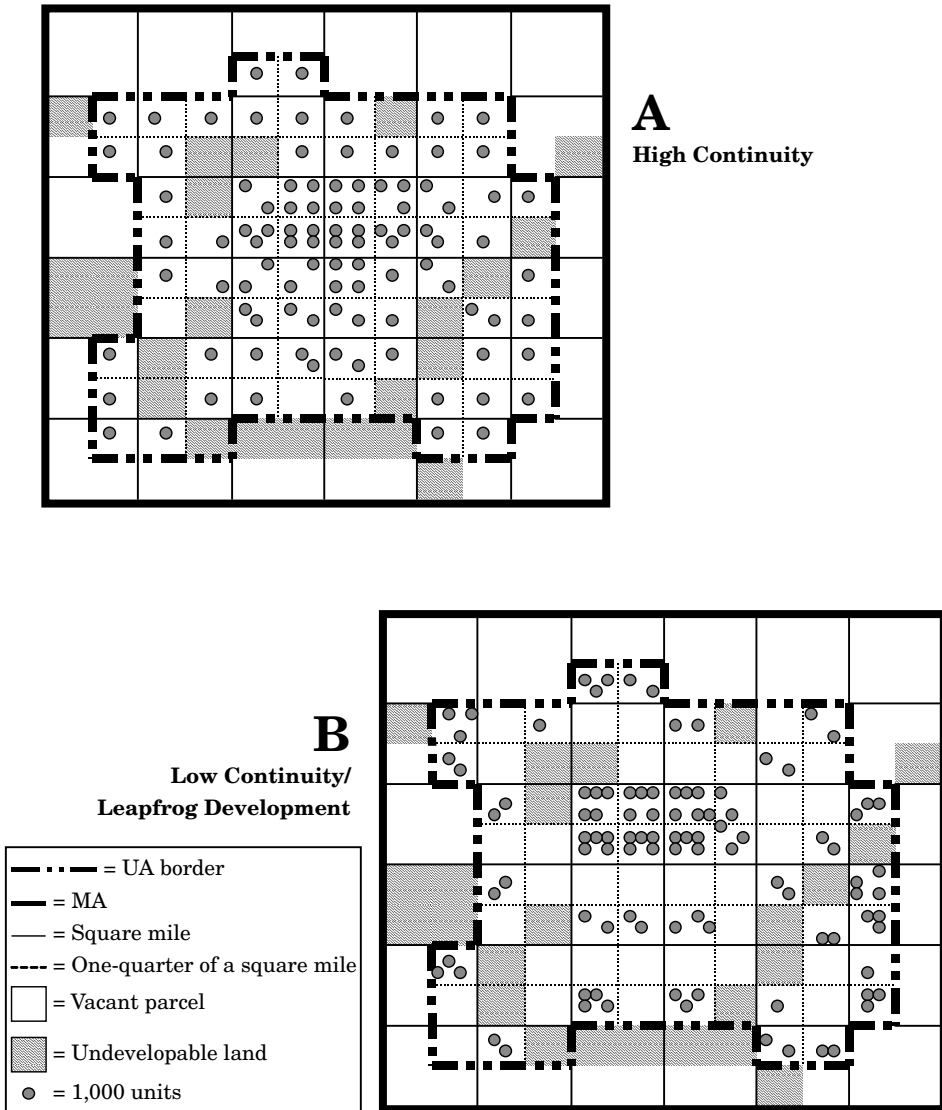
## Concentration

Concentration is the degree to which development is located disproportionately in relatively few square miles of the total UA rather than spread evenly throughout.

An urban area may be continuously developed, but no urban area is ever evenly developed. The density dimension does not tell us anything about how residential uses are distributed. The same 100-square-mile area with 500,000 residences and 200,000 jobs would have an average residential density of 5,000 units per square mile and an average employment density of 2,000 jobs per square mile. The homes and jobs could be distributed in an almost infinite number of arrangements with equal degrees of continuity.

The concentration dimension distinguishes those urban areas in which most housing units and employment are located in relatively few places at relatively high densities from those in which development is more evenly distributed across the urban landscape, as illustrated by figure 3. With the same amount of development in each diagram, A is more highly concentrated than B, where development is more evenly distributed. With lower concentration, B's development pattern is more sprawl-like on this dimension.

*Figure 2.* **Continuity: The Degree to Which Developable Land Has Been Built Upon at Urban Densities in an Unbroken Fashion**



**A**

**High Continuity**

**B**

**Low Continuity/ Leapfrog Development**

= UA border

= MA

= Square mile

= One-quarter of a square mile

= Vacant parcel

= Undevelopable land

= 1,000 units

## *Clustering*

Clustering is the degree to which development has been tightly bunched to minimize the amount of land in each square mile of developable land occupied by residential or nonresidential uses.

Sprawl is frequently used as an antonym for development that is stacked or clustered so that its footprint occupies only a small portion of the land area associated with it (Gordon and Richardson 1997). We empha-

*Figure 3.* **Concentration: The Degree to Which Development Is Located in Relatively Few Square Miles Rather Than Spread Evenly across the UA**
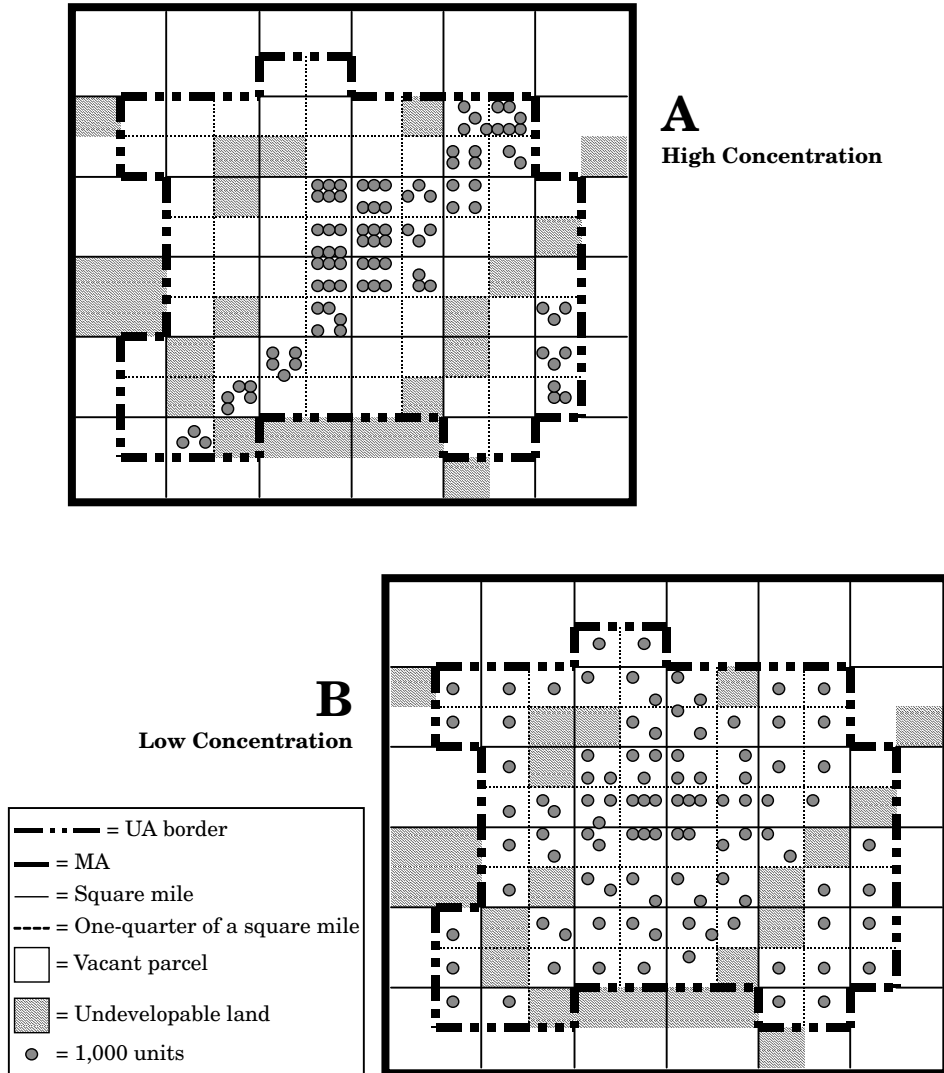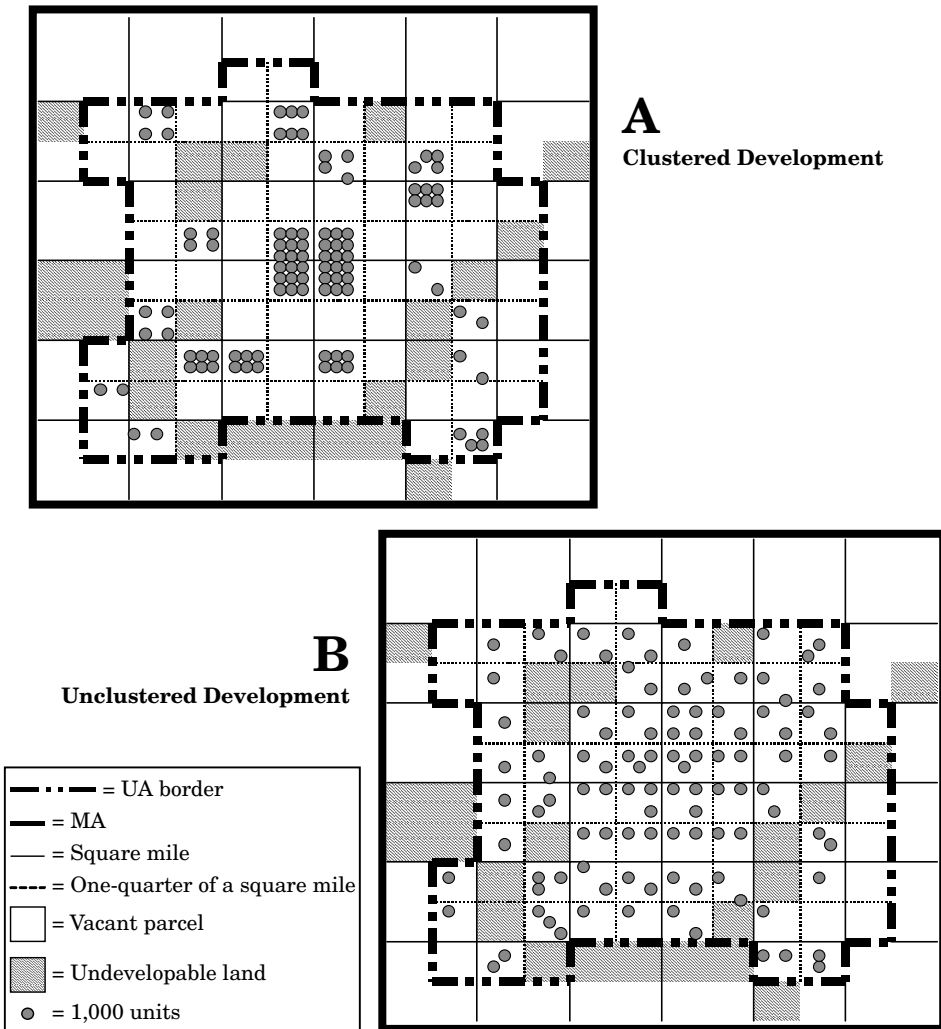


size that clustering is a distinct dimension of land development. Unlike density and concentration, which are concerned with development patterns *across* grids, clustering is concerned with the footprint of development patterns *within* grids. Development may be dense and concentrated and still not be clustered (because it is uniformly spread within all grids, high- and low-density ones alike). Conversely, a UA may have low densities and a low concentration, but clustering may be high if whatever urbanized uses there are within a grid are tightly bunched.

Low clustering is a dimension that has been linked to several alleged effects, such as the creation of impervious surfaces that contribute to

flooding and erosion. Clustered development may also reduce travel distances within a development, but not necessarily between home and work if they are situated in different parts of the area.

In figure 4, the development in A has been clustered so that it occupies half or less than half of the land area in each of the large squares. In B, the same amount of development in each large square is more evenly distributed. Thus B's development is more sprawl-like overall on this dimension.

*Figure 4.* **Clustering: The Degree to Which Development Has Been Tightly Bunched to Minimize the Amount of Land in Each Square Mile of Developable Land Occupied by Units of Residential or Nonresidential Use**



**A**
**Clustered Development**

**B**
**Unclustered Development**

- —··—··— = UA border
- —— = MA
- —— = Square mile
- ---- = One-quarter of a square mile
- ☐ = Vacant parcel
- ▨ = Undevelopable land
- ● = 1,000 units

## *Centrality*

Centrality is the degree to which residential or nonresidential development (or both) is located close to the central business district (CBD) of an urban area.

Loss of centrality is one of the most common laments about sprawl. Generally, this refers to the extent to which development has diffused across the landscape from the historic core or CBD of an urban area. Decentralization of urban areas is often cited as a cause for longer travel distances and times and inefficiencies in land use. The centrality of a UA increases as the radius from the CBD within which the greater proportion of development is located shortens. Conversely, an area will exhibit greater sprawl where greater distances from the center are required to contain the same proportion of development. Figure 5 depicts a highly centralized area and another with a low level of centralization and, thus, more of this dimension of sprawl.

## *Nuclearity*

Nuclearity is the extent to which an urban area is characterized by a mononuclear (as opposed to a polynuclear) pattern of development.
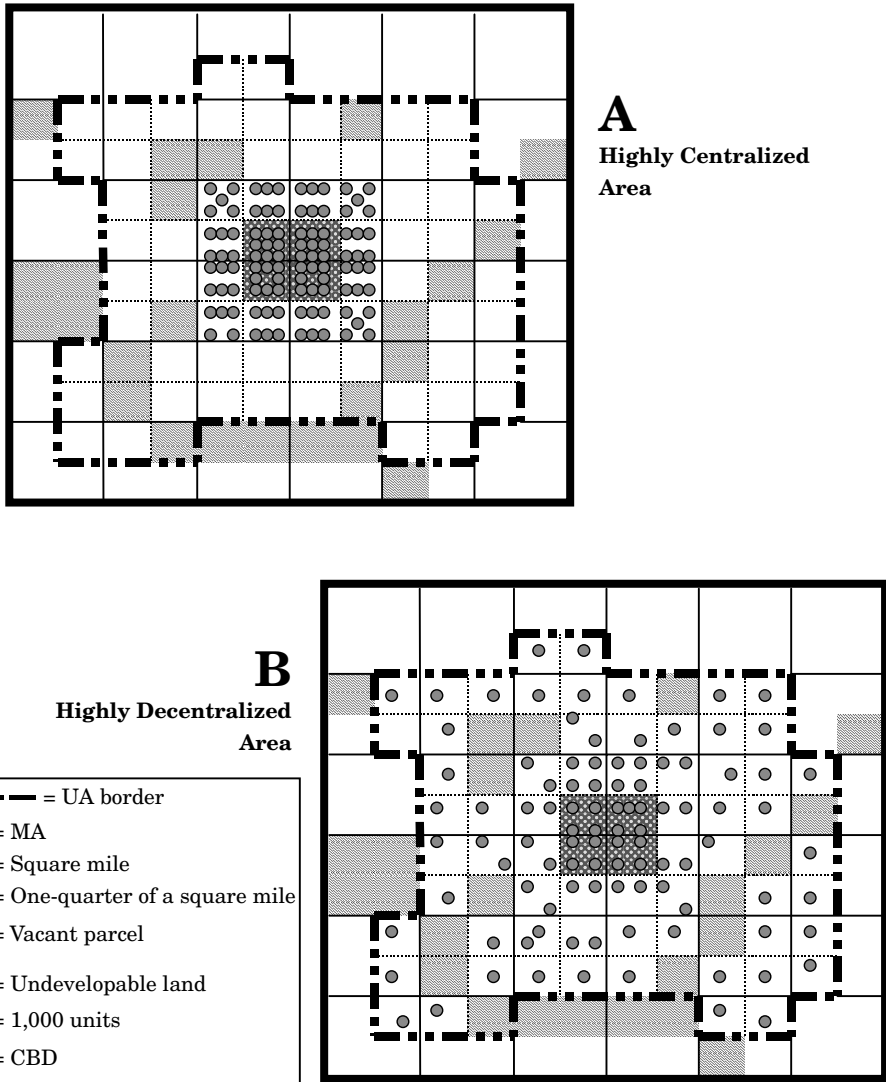
Centrality is a measure best suited to mononuclear urban areas. Increasingly, U.S. urban areas have become polynuclear as historic CBDs have declined in relative or even absolute terms, outlying centers and edge cities have grown in scale, and different centers have taken on more specialized functions, such as financial centers, technology centers, retail, or manufacturing hubs.

If its CBD is the only locus of intense development, an area will have a mononuclear structure, and its nuclearity is maximized. If the same activities are dispersed over several intensely developed places and each contains an agglomeration of activities that represent a substantial proportion of the total of such activities in the region, it is polynuclear.

Nuclearity and concentration need not be closely related. A UA may only have one nucleus or many nuclei, but if their densities are not significantly greater than the average density of the rest of the UA, concentration will be low. Similar logic leads one to the conclusion that nuclearity is conceptually distinct from our other dimensions of sprawl as well.

Nuclearity is an important dimension. A polynuclear pattern may reduce costs for some people by shortening their journey to work, but it may increase other costs, such as land values in the vicinity of major employment nodes.

*Figure 5.* **Centrality: The Degree to Which Development in a UA
Is Located Close to the CBD**



**A**
**Highly Centralized
Area**

**B**
**Highly Decentralized
Area**

---- = UA border
— = MA
— = Square mile
---- = One-quarter of a square mile
☐ = Vacant parcel
▨ = Undevelopable land
● = 1,000 units
▨ = CBD

In figure 6, A illustrates a mononuclear UA and B represents a polynu-
clear area.

*Mixed uses*

Mixed uses means the degree to which two different land uses com-
monly exist within the same small area, and this is common across
the UA.

*Figure 6.* **Nuclearity: The Extent to Which a UA Is Characterized by a Mononuclear or Polynuclear Pattern of Development**
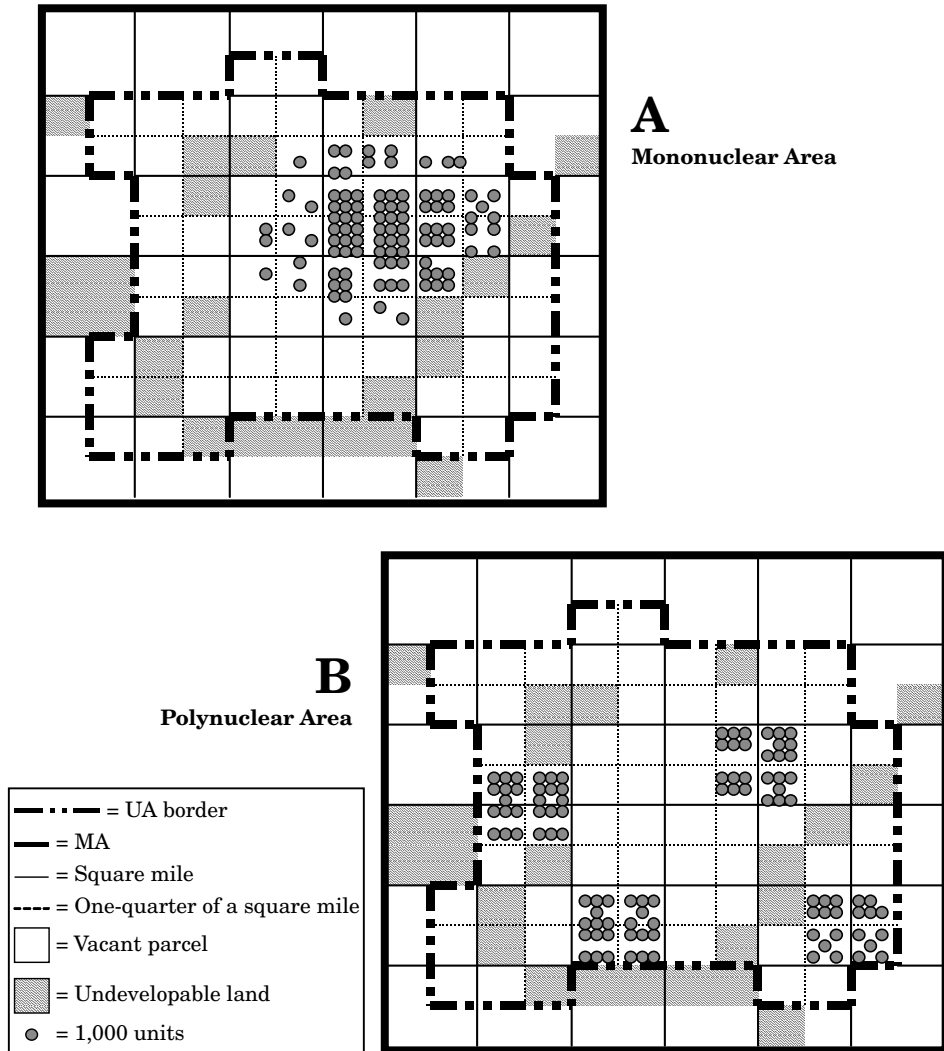


Another feature attributed to sprawl is the separation of different kinds of land uses from each other (Vermont Forum on Sprawl 1999) and the income segregation of suburban residential developments, due primarily to minimum lot sizes in different zoning categories (Burchell et al. 1998; Cervero 1991; Downs 1999; GAO 1999; Orfield 1997; Sierra Club 1998). The complaint is that sprawl either causes or is caused by patterns of exclusive land use, including separation of homes, workplaces, and conveniences, as well as income segregation among residential communities. As the mixture of uses in a community declines, travel time and distance for those who live or work there increase. If exclusivity of use in small areas is typical of an entire UA, one would expect an increase in

the inconveniences often attributed to sprawl, such as traffic congestion, trip length, and travel times.

Mixed land uses, or the lack thereof, is often inferred from some measure of accessibility, such as vehicle miles traveled or time spent in travel. Such measures, however, do not distinguish between the extent to which they result from exclusive or mixed land uses or other factors, such as household behavior. As before, we argue that it is crucial to distinguish the mixture of land uses within a grid (which can be measured directly) from the consequences of that pattern.

Figure 7 illustrates such an approach. In A, every square contains an equal proportion of the UA's residences and employment. Moreover, this pattern of a high level of mixed use is typical of the entire area. In B, each square contains only a single land use and represents the lowest degree of mixed use; it is therefore more sprawl-like on this dimension.
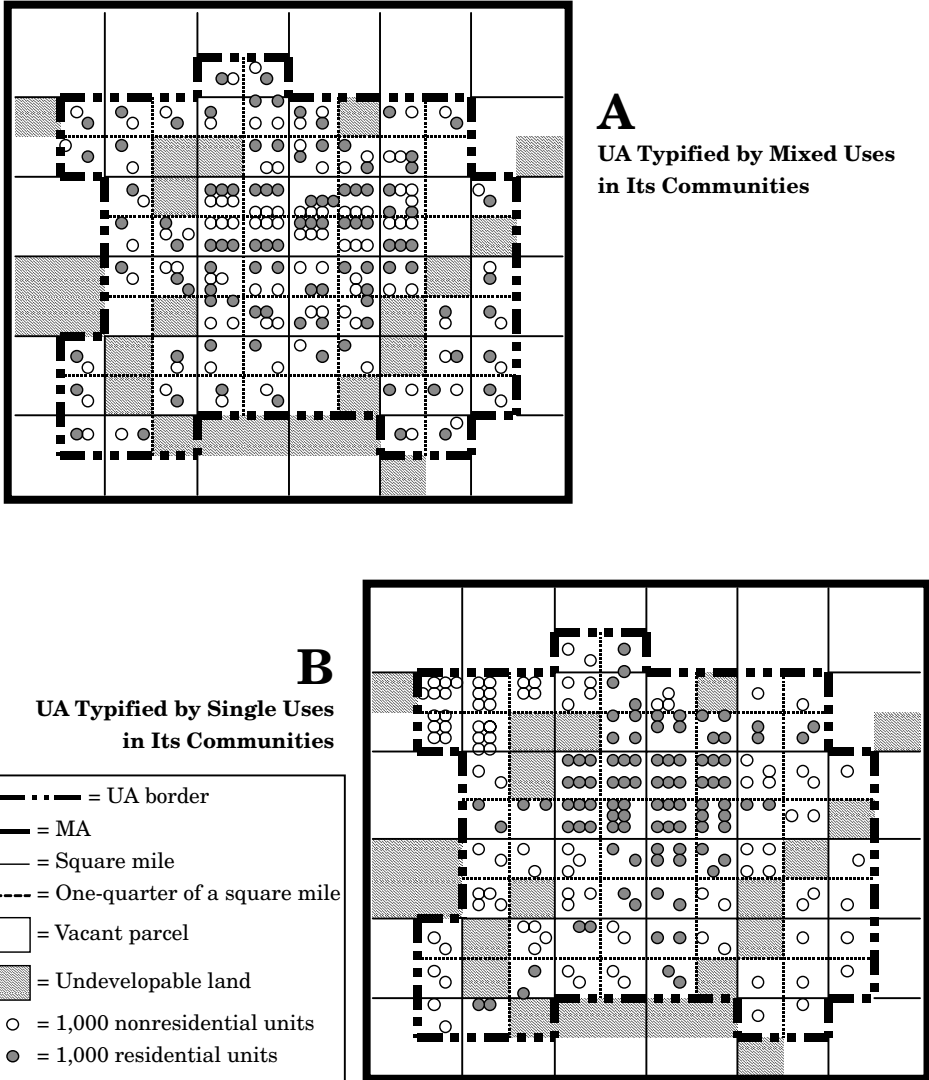
### Proximity

Proximity is the degree to which different land uses are close to each other across a UA.

The mixed-use dimension of development patterns captures only the extent to which small parts of a UA are typically devoted exclusively to a single use. Proximity is the dimension that establishes the typical distance between different uses. For example, the extent to which jobs and housing for low-income workers are spatially mismatched affects economic opportunity. And the average distance workers must travel for employment, or consumers must travel to shop for convenience or comparison goods, contributes to many of the externalities attributed to sprawl.[2] While proximity of the same uses to each other is a significant feature in the agglomeration of related activities in urban space, that seems a less significant feature of sprawl than the proximity of different but complementary uses, such as housing and employment or consumer goods.

Conceptually, proximity is the average distance people must travel from any "home" or residential square to every other "target" or employment square. Those UAs where most people must travel great distances have lower proximity between uses and, therefore, can be considered to exhibit more sprawl. In figure 8, A illustrates an urban area with high proximity of land uses, and B illustrates one with low proximity.

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[2] It may make sense to measure proximity between various types of nonresidential uses if workers often travel among them.

*Figure 7.* **Mixed Uses: The Degree to Which Two Different Land Uses
Exist in the Same Small Area and This Pattern
Is Typical throughout the UA**



**A**

**UA Typified by Mixed Uses
in Its Communities**

**B**

**UA Typified by Single Uses
in Its Communities**

|  |  |
|---|---|
| – ·· – ·· – | = UA border |
| ▬▬ | = MA |
| ──── | = Square mile |
| ------ | = One-quarter of a square mile |
| ☐ | = Vacant parcel |
| ▨ | = Undevelopable land |
| ○ | = 1,000 nonresidential units |
| ● | = 1,000 residential units |

## Proposed operationalization of the dimensions of sprawl
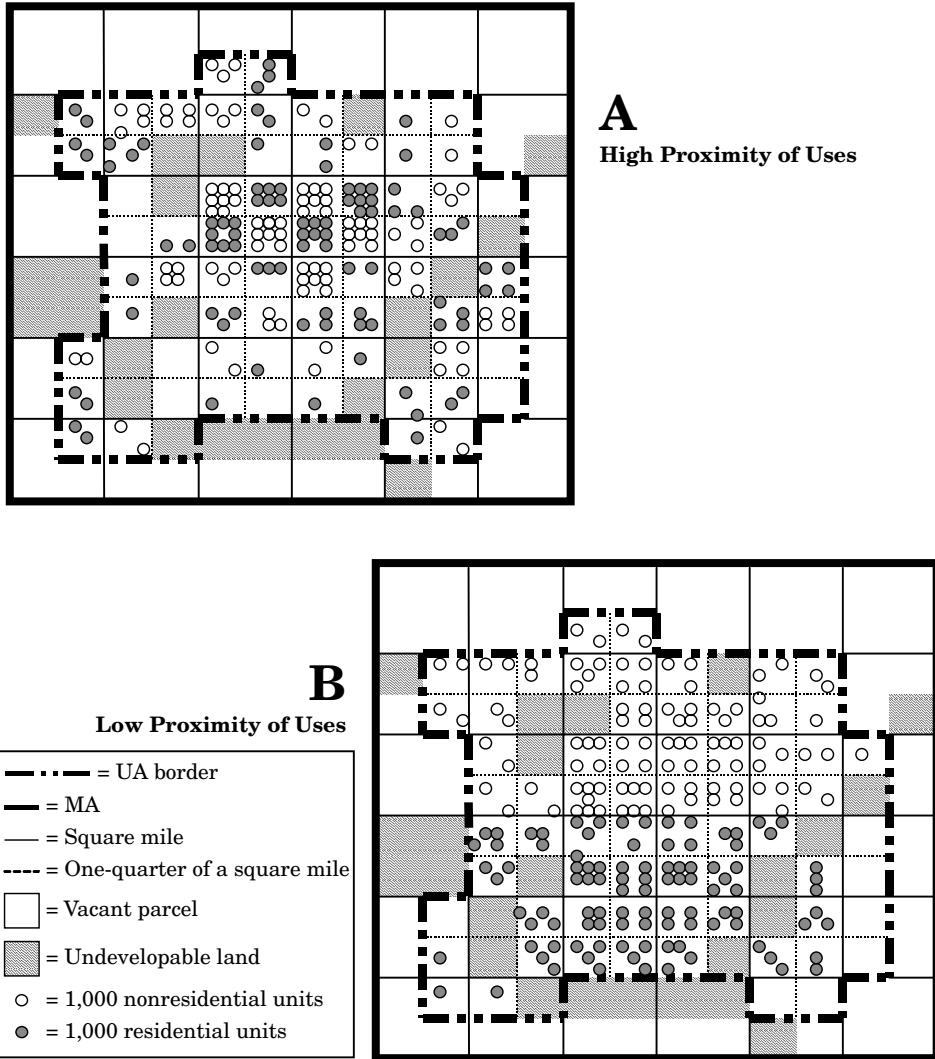
The next step in our research plan is to operationalize the foregoing dimensions of sprawl.

We first divide land use into three types: residential, nonresidential (although in principle nonresidential could be further subdivided), and nondevelopable. In some of our dimensions, the appropriate operationalization considers only *developable* land; that is, land that is nondevel-

*Figure 8.* **Proximity: The Degree to Which Different Land Uses**
**Are Close to Each Other across a UA**



**A**

**High Proximity of Uses**

**B**

**Low Proximity of Uses**

| | |
|---|---|
| — · · — | = UA border |
| ▬▬ | = MA |
| —— | = Square mile |
| ---- | = One-quarter of a square mile |
| □ | = Vacant parcel |
| ▨ | = Undevelopable land |
| ○ | = 1,000 nonresidential units |
| ● | = 1,000 residential units |

opable because of natural features, public use, or regulatory barriers is
excluded.[3] We superimpose on all land within the UA a series of one-
mile squares and, within these one-mile squares, a set of four one-half-
mile squares (one-fourth of a square mile each). Depending on the di-

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[3] This inconsistency is justifiable on conceptual grounds. For example, residential den-
sity should be computed using only developable acreage so as not to unfairly charac-
terize as more sprawled UAs with more mountains, floodplains, or parklands. Howev-
er, for proximity or centrality, it is appropriate to measure distances between locations
using all intervening acreage, whether developable or not, since such land must be
traversed regardless.

mension, the geographic units of analysis we employ are either these one-mile-square grids or the one-half-mile-square grids.

We now turn to the operationalization of the eight dimensions. More detailed nomenclature and formulas are presented in appendix A.

### Density

*Definition*: The average number of residential units or the average number of employees per square mile of developable land in a UA.

*Unit of analysis*: One-mile-square grids.

*Operationalization*: Total number of housing units (or employees) in a UA/area of a UA.

### Continuity

*Definition*: The degree to which *developable* land has been developed in an unbroken fashion throughout the UA.

*Unit of analysis*: One-half-mile-square grids.

*Operationalization*: A one-half-mile-square grid is considered developed if it contains 10 or more housing units or 50 or more employees. The proportion of all such grids in the UA that are so developed is a measure of continuity.

### Concentration

*Definition*: The degree to which housing units or jobs are disproportionately located in a relatively few areas or spread evenly in the UA.

*Unit of analysis*: One-mile-square grids.

*Operationalization*: Three potential measures.

1.  Very high density grids (with respect to housing units or employees) as a percentage of all grids with developable land within the UA. Very high density grids are two standard deviations or more above the mean of the density of all grids in the 100 largest UAs (or in a sample of the 100 largest UAs).

2. The coefficient of variation (standard deviation divided by the mean) of the density of housing units or employees among the grids of scale *m* in a UA.

3. Delta index. This is analogous to the dissimilarity index and can be interpreted as the share of land use *i* (e.g., housing units) that would need to shift areal units of scale *m* to achieve a uniform distribution across the UA (Massey and Denton 1988). Higher values of DELTA indicate more concentration of a use in certain subareas, thus less sprawl.

## Clustering

*Definition*: The degree to which development within any one-mile-square area is clustered within one of the four one-half-mile squares contained within (as opposed to spread evenly throughout).

*Units of analysis*: One-half-mile- and one-mile-square grids.

*Operationalization*: The average for all one-mile squares of the standard deviations of the density of a particular land use (e.g., housing units or employees) among the four squares of each one-mile grid with developable land, standardized by the average density across *m*-scale grids.

## Centrality

*Definition*: The degree to which observations of a given land use are located near the CBD of a UA.

*Unit of analysis*: One-mile-square grids.

*Operationalization*: Two measures. In both, the CBD is defined as the address of city hall.

1. The average distance of a land use (e.g., housing units) from the CBD. This is measured as the inverse of the average of the sum of the distance from the center of the CBD grid to the center of each one-mile-square grid weighted by the number of observations of the land use (e.g., housing units) in the grid, with the resulting average standardized by the square root of the area of the UA. Lower values therefore reflect more sprawl.

2. A centralization index that measures how rapidly a given land use accumulates relative to land area as one moves progressively outward in concentric rings from the CBD (Massey and Denton 1988).

The centralization index is computed in the following way. With Geographic Information Systems software, one draws a series of concentric rings (bulls-eye style) from the CBD center (say, using one-mile radii). Then, one essentially compares how fast population or any land use in question accumulates, starting at the innermost ring and working progressively outward. This cumulative distribution is compared with the corresponding cumulative distribution of urbanized land area as a baseline.

If virtually all of the observations of a particular land use accumulate within, say, the innermost two rings but these rings represent only a small fraction of the UA, centrality will register a high value. At the other extreme, if few uses are located near the center but most are instead near the edge, land area will accumulate faster than the particular land use moving outward, and centrality will have a low (negative) value, signifying a greater degree of sprawl on this dimension.

## Nuclearity

*Definition*: The extent to which a UA is characterized by a mononuclear pattern of development.

*Unit of analysis*: One-mile-square grids.

*Operationalization*: Nuclearity involves the identification of nodes or nuclei by means of the following steps:

1.  Identify the highest density (in terms of both housing units and, separately, employees) per one-mile-square grid in the UA.

2.  Add all adjacent grids that are within one standard deviation of the density of this highest-density grid to the node; also include nodes adjacent to the added nodes, provided they are within one standard deviation of the highest-density grid. The result is the central node, $c$.

3.  Recalculate the density of the newly combined highest-density nucleus $c$ (per #2).

4.  Consider all other one-mile-square grids in the UA that are within one standard deviation of the recalculated density (per #3) as separate nuclei, $n$, provided that they are not immediately adjacent to an existing nucleus.

5.  Add any grids adjacent to any nucleus identified in #4 that are within one standard deviation of the recalculated highest-density nucleus $c$ (per #3) to the nucleus.

*Measurement*: Two measures.

1.  The number of nodes (a measure of the degree of polynuclearism).

2.  The number of observations (housing units or employees) in the central (highest-density) nucleus as a percentage of the number of observations in all of the nuclei (a measure of mononuclearity).

## Mixed uses

*Definition*: The degree to which substantial numbers of two different land uses (e.g., housing units and employees) exist within the same area and this pattern is typical throughout the UA.

*Units of analysis*: One-mile-square grids.

*Operationalization*: To operationalize this concept, we employ a version of Massey and Denton's well-known exposure index (1988). The intuitive interpretation of this index is the average density of a particular land use (e.g., housing units) in another land use's (e.g., nonresidential or employees) area.

## Proximity

*Definition*: The degree to which a particular land use or pair of land uses are close to each other across the UA.

*Unit of analysis*: One-mile-square grids.

*Operationalization*: This measure can be defined not only for a given use (average distance between households, between jobs, etc.) but, potentially more interesting, *between* uses. For example, one can define proximity between households and jobs as the measure of sprawl most closely associated with spatial mismatch.

*Measurement*: The measures we propose are adaptations of indices developed by White (1986). We first compute the weighted average distance in the UA between a given land use $i$ and all observations of another use $j$ (including the possibility that $i = j$). We sequentially take each distance between a centroid of a given one-mile-square area $m$ and the centroid of another one-mile-square area $k$ and weight it by the proportion of the land use of interest $j$ in the UA represented by the target area $k$. This is done using grid area $m$'s centroid as the origin and computing the weighted distance to every other area's centroid until all of

the weighted distances are summed to get the average.[4] This procedure is then repeated for all one-mile-square areas as the origin point of distances; all these observations are weighted by the proportion of the UA's share of land use $i$ represented in grid area $m$.

## Testing our definitions: Measuring housing sprawl in 13 UAs

We are now ready to test the foregoing operationalized definitions of dimensions of sprawl by applying them to a small number of UAs in the United States. We selected 13 large areas from different regions of the country for our prototype test. Because of both resource and time constraints, our test is confined to residential uses; we thus examine in the following section only housing sprawl, with housing units as the land use for our analysis.[5] Because of this, we will not be able to test our operationalizations for interuse measures, continuity, and diversity. In addition, given our constraints, we were unable to separate out developable from nondevelopable land; as a consequence, all land is considered developable.

### *Method*

Each of the 13 UAs was first divided into one-mile-square grids, including those that were only partially in the UA.[6] Each grid was then divided into four one-half-mile-square grids. A Geographic Information System was used to estimate the fraction of each grid within the UA, and this value, including the latitude and longitude of the grid's centroid, was entered into the database. Then, 1990 census block data for housing units were aggregated to create a count for each grid.[7] (See appendix B for a technical explanation.)

We next computed a value for each of the 13 UAs on each of the six dimensions we included: density, concentration, clustering, centrality, nuclearity, and proximity. The computation formulas are summarized in

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[4] Note that when $k = m$, distance = 0.

[5] For an examination of land use patterns for offices, see Lang (2000a).

[6] For the clustering measure, only grids that were wholly in the UA were used, thus eliminating those that were partially in the UA but also included clearly nondevelopable area such as lakes, rivers, etc. This was mandated because of the artificially high density variance of such boundary grids. Otherwise, cities on large bodies of water would register less clustering ante facto than landlocked cities.

[7] Blocks split by grid boundaries were assigned to the grid containing the largest share of the block.

appendix A. For concentration, we employed the delta index as described in the Operationalization section (operationalization #3 under Concentration in appendix A). For centrality, we used the weighted average distance from city hall calculation (operationalization #1 under Centrality in appendix A). None of our proposed operationalizations worked well for nuclearity, possibly because we attempted to measure housing rather than employment nuclearity. Our proposed measure (including as nodes all those grids within one standard deviation of the densest grid or set of grids) yielded almost no nodes other than the central one. Instead, we adopted a second-best operationalization that gave us a useful measure of residential mononuclearity: the percentage of all housing units in the 2 percent of the densest grids in the UA that are located in the central node, with the central node consisting of all grids in the densest 2 percent of the grids that are contiguous and nearest city hall. For proximity, we used the intrause measure, since we had only data for residential land use.

After measuring and comparing the 13 areas on six dimensions of sprawl, we will see how the results comport with our firsthand knowledge of these areas, as well as the conventional wisdom.

## *Results*

Table 1 reports the raw scores for each of the 13 UAs on each of the six dimensions.

Inasmuch as our sample of 13 UAs is not large enough to permit factor analysis, we created a series of "Z scores." (A Z score is simply the number of standard deviations a UA is from the mean of the distribution for

*Table 1.* **Indicators of Urban Sprawl**

|  | Density | Concentration | Clustering | Centrality | Nuclearity | Proximity |
|---|---|---|---|---|---|---|
| Mean | 1,407.42 | 0.39 | 0.44 | 167.46 | 62.84 | 0.28 |
| Standard deviation | 389.56 | 0.06 | 0.06 | 25.36 | 25.71 | 0.07 |
| Atlanta | 806.25 | 0.28 | 0.38 | 177.86 | 44.17 | 0.2569 |
| Boston | 1,000.63 | 0.47 | 0.44 | 191.83 | 88.80 | 0.2754 |
| Chicago | 1,647.09 | 0.40 | 0.49 | 160.30 | 82.42 | 0.3392 |
| Dallas | 901.57 | 0.41 | 0.47 | 149.40 | 24.03 | 0.3311 |
| Denver | 1,462.90 | 0.31 | 0.41 | 178.22 | 67.40 | 0.1656 |
| Detroit | 1,265.60 | 0.34 | 0.39 | 141.51 | 69.94 | 0.2610 |
| Houston | 989.45 | 0.40 | 0.54 | 183.16 | 13.44 | 0.2539 |
| Los Angeles | 1,861.84 | 0.37 | 0.36 | 166.97 | 57.92 | 0.3800 |
| Miami | 1,883.26 | 0.32 | 0.41 | 125.91 | 43.79 | 0.1793 |
| New York | 1,946.48 | 0.51 | 0.51 | 202.24 | 96.56 | 0.4048 |
| Philadelphia | 1,483.97 | 0.41 | 0.52 | 192.14 | 89.98 | 0.2551 |
| San Francisco | 1,639.00 | 0.43 | 0.37 | 124.76 | 78.42 | 0.3041 |
| Washington, DC | 1,408.43 | 0.36 | 0.44 | 182.74 | 60.06 | 0.2384 |

that dimension.) Each UA thus has a Z score for each of the six dimensions. We then added the Z scores for each UA across all six dimensions to obtain a composite sprawl index. This weights each of the dimensions equally in calculating the index. (Analysts may choose to recompute our aggregate scores using their own weighting schemes based on the constituent scores presented.) The Z scores for each dimension and the composite sprawl index are presented in table 2. Since more sprawl-like conditions are rated low and less sprawl-like conditions high on each of the dimensions, higher Z scores reflect lower levels of sprawl.

The UAs with the greatest degree of sprawl—i.e., the lowest score on the composite index—were Atlanta, followed by Miami, Detroit, and Denver. The UAs with the lowest degree of sprawl were all older areas in the Northeast and Midwest: The New York area had the least sprawl, followed by Philadelphia, Chicago, and Boston. This comports with the pre-20th-century development of their cores. Atlanta and Miami represent the archetypes of what Lang (2000b) calls "wet south region sprawl," where 20th-century growth has been unconstrained by the aridity of the region. Los Angeles, often cited as the prototype for auto-spawned sprawl, had the fifth-lowest degree of sprawl on the composite index. Our interpretation of the relative ranking of Los Angeles is that the conventional wisdom with respect to the degree of its sprawl relative to other areas may simply be wrong. Natural attributes like topography and aridity have apparently constrained land use patterns more than is usually understood (Lang 2000b).

It is possible that an extreme score on one or two dimensions may be driving the overall value of the composite index. To test this, we ranked each UA on each of the six dimensions and then summed across dimensions. (Additional means of weighting to compute the aggregate ranking are possible; ours is merely illustrative.) The top rank meant the lowest sprawl-like value on that dimension. Thus, the area with the lowest summary ranking score (New York) had the least sprawl (see table 3). Using this method led to very little change in the composite index: Only one area, Washington, DC, which moved from the sixth-lowest to the eighth-lowest degree of sprawl, moved more than one place in the rankings.

Table 3 allows us to more easily observe the extent of variation across the dimensions. Areas with low sprawl rankings on some dimensions did not necessarily have consistently low rankings overall. Philadelphia, for example, with the second-lowest ranking for overall sprawl, also ranked second in terms of clustering, centrality, and mononuclearity, but ninth with respect to proximity. Los Angeles, with the fifth-lowest ranking overall, ranked second lowest in sprawl with respect to density and proximity, but last with respect to clustering. Even Atlanta, which had the most sprawl in the overall ranking, ranked only seventh on the centrality dimension and eighth on proximity.

*Table 2.* **Urban Sprawl Indicators: Z Scores**

| | Density | Concentration | Clustering | Centrality | Nuclearity | Proximity | Composite Index | Rank |
|---|---|---|---|---|---|---|---|---|
| New York | 1.38 | 1.92 | 1.14 | 1.37 | 1.31 | 1.77 | 8.90 | 1 |
| Philadelphia | 0.20 | 0.38 | 1.31 | 0.97 | 1.06 | -0.36 | 3.56 | 2 |
| Chicago | 0.62 | 0.23 | 0.81 | -0.28 | 0.76 | 0.84 | 2.97 | 3 |
| Boston | -1.04 | 1.31 | -0.01 | 0.96 | 1.01 | -0.07 | 2.15 | 4 |
| Los Angeles | 1.17 | -0.24 | -1.34 | -0.02 | -0.19 | 1.42 | 0.80 | 5 |
| Washington, DC | 0.00 | -0.39 | -0.01 | 0.60 | -0.11 | -0.60 | -0.50 | 6 |
| San Francisco | 0.59 | 0.69 | -1.17 | -1.68 | 0.61 | 0.34 | -0.63 | 7 |
| Houston | -1.07 | 0.23 | 1.64 | 0.62 | -1.92 | -0.38 | -0.89 | 8 |
| Dallas | -1.30 | 0.38 | 0.48 | -0.71 | -1.51 | 0.72 | -1.94 | 9 |
| Denver | 0.14 | -1.16 | -0.51 | 0.42 | 0.18 | -1.63 | -2.56 | 10 |
| Detroit | -0.36 | -0.70 | -0.84 | -1.02 | 0.28 | -0.28 | -2.93 | 11 |
| Miami | 1.22 | -1.01 | -0.51 | -1.64 | -0.74 | -1.44 | -4.11 | 12 |
| Atlanta | -1.54 | -1.63 | -1.00 | 0.41 | -0.73 | -0.33 | -4.83 | 13 |

*Table 3.* **Ranking of Urban Sprawl Indicators**

| | Density | Concentration | Clustering | Centrality | Nuclearity | Proximity | Total | Rank |
|---|---|---|---|---|---|---|---|---|
| New York | 1 | 1 | 3 | 1 | 1 | 1 | 8 | 1 |
| Philadelphia | 6 | 4 | 2 | 2 | 2 | 9 | 25 | 2 |
| Chicago | 4 | 6 | 4 | 9 | 4 | 3 | 30 | 3 |
| Boston | 10 | 2 | 6 | 3 | 3 | 6 | 30 | 3 |
| Los Angeles | 2 | 8 | 13 | 8 | 9 | 2 | 42 | 5 |
| San Francisco | 5 | 3 | 12 | 13 | 5 | 5 | 43 | 6 |
| Houston | 11 | 6 | 1 | 4 | 13 | 10 | 45 | 7 |
| Washington, DC | 8 | 9 | 6 | 5 | 8 | 11 | 47 | 8 |
| Dallas | 12 | 4 | 5 | 10 | 12 | 4 | 47 | 8 |
| Denver | 7 | 12 | 8 | 6 | 7 | 13 | 53 | 10 |
| Detroit | 9 | 10 | 10 | 11 | 6 | 7 | 53 | 10 |
| Miami | 3 | 11 | 8 | 12 | 11 | 12 | 57 | 12 |
| Atlanta | 13 | 13 | 11 | 7 | 10 | 8 | 62 | 13 |

Further evidence that our six operationalizations of the dimensions of sprawl are indeed related to the same core construct yet are quite independent is provided by a correlation analysis.[8] Pearsonian correlations among the six revealed only three that were statistically significantly different from zero: proximity and concentration (0.65), centrality and clustering (0.53), and clustering and concentration (0.52). Across all indicators, the correlations averaged 0.29.[9]

## Summary and next steps

Each dimension of urban land use we have defined is conceptually distinct from each of the others. Each is a condition of land use that can be observed. Each is free of judgment about its intrinsic value. And as an objective condition, each is independent of those policies, practices, or preconditions that may have caused it or of those things that may be consequences of its existence. Each dimension can be measured on a continuum and compared across UAs. Individually and in combination, low scores on the dimensions correspond to intuitive understanding and general observations about the extent of sprawl in the UAs to which they were applied. Moreover, the rankings do not appear to be unreasonable.

This exercise also reveals the need for some refinements. Conceptually, more work is needed to define an appropriate study area that includes related sprawl-type development located beyond the UA and functionally attached to it without encompassing large areas that are genuinely rural in character. A precise definition of undevelopable land would improve the measurement of some dimensions. Simplification of some of our measures to increase their transparency would be desirable if it can be done without impairing their effectiveness. And it will be important to develop measures of nonresidential development.

Our prototype test of operational measures of housing sprawl proved encouraging. With improvements identified by this effort, a conceptually clearer and more coherent set of sprawl measures is attainable for a large set of MAs. This would permit using statistical techniques such as factor analysis to determine the extent to which dimensions are associated most closely with others and to develop indices that combine some or all of the dimensions. The objective of this sort of analysis should be to specify several different types of sprawl—indicated by low values on related dimensions of the eight urban development patterns—and to produce an overall sprawl index for UAs.

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[8] This analysis is available from the first author on request.

[9] There were two negative correlation coefficients: density and compactness (–0.09) and density and centrality (–0.17). However, both fell far short of the value needed for 0.05 statistical significance for such a sample size: 0.51.

The resulting typologies and indices can then be used as independent variables in research that examines the effect of different degrees or types of sprawl on the spatial distribution of income in MAs, the incidence of poverty, or externalities of urban growth patterns. The respective dimensions and types of sprawl can be compared to determine which, if any, have a greater effect on variables that are considered to be consequences of sprawl, and sprawl can be compared with other variables to determine their relative power to explain urban conditions. As dependent variables, specific dimensions can help identify policies and practices that tend to induce particular land use patterns.

Conceptual clarity about the dimensions of sprawl and the ultimate operationalization of these concepts should thus make it possible to inform policy far more effectively as officials attempt to affect the causes of the several dimensions or grapple with their consequences. It should also be possible to measure sprawl for one or more individual areas, or even parts of areas such as counties, in a time series that can permit informed inferences about the effectiveness of policies and practices designed to manage urban development and its consequences.

*Appendix A*

*Formal operationalization of the dimensions of sprawl*

## Nomenclature

Let

$i$ = a particular type of land use or spatially based observation, in our case, either residential use (for which we use housing units) or nonresidential use (for which we use employees).

$j$ = a different type of land use from $i$.

$u$ = the largest spatial scale used in the analysis; the entire UA.

$m$ = the medium spatial scale used in the analysis: one square mile; 1, 2, …, $m$, …, $M$ such medium-sized squares comprise the UA $u$.

$s$ = the smallest spatial scale used in the analysis: one-quarter of a square mile (a square with a half-mile per side); 1, 2, …, $s$, …, $S$ such small-sized squares comprise the UA $u$ [10]

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[10] Using grids of any size produces some distortion in results because of the arbitrary location of the grid lines. There is a need, however, for a common metric that can be applied across all areas. The use of one-mile-square and one-quarter-mile-square grids provides a scale that can be readily understood and visualized.

*T(i)u* = the total number of observations (population) of land use *i* in UA *u*.

*T(i)m* = the total number of observations (population) of land use *i* in land area *m* (that is also within *u*).

*T(i)s* = the total number of observations (population) of land use *i* in land area *s* (that is also within *u*).

*Pm* = proportion of land area of spatial scale *m* within *u*.

*Ps* = proportion of land area of spatial scale *s* within *u*.

*Au* = the total developable land area within UA *u*; $= \sum\limits_{m=1}^{M} Pm \, (Am)$.

*Am* = the total developable land area within a grid of spatial scale *m = Pm*.

*As* = the total developable land area within a grid of spatial scale *s* = 0.25*Ps*.

*D(i)u* = the density of land use *i* over the developable UA = *T(i)u / Au*.

*D(i)m* = the density of land use *i* over the developable area in *m* = *T(i)m / Am*.

*D(i)s* = the density of land use *i* over the developable area in *s* = *T(i)s / As*.

*F[k,m]* = the distance between the centroids of grid *k* and grid *m*.

Given this nomenclature, we turn to how each of our dimensions can be formally operationalized.

## Density

$$\text{DENS}(i)u = D(i)u = T(i)u / Au = \sum\limits_{m=1}^{M} [T(i)m] / Au \tag{1}$$

[min = 1,000 per square mile (U.S. Bureau of the Census standard for a UA); max = unlimited]

## Continuity

$$\text{CONT}(i)u \ \overset{S}{\underset{s=1}{\Sigma}} \ [D(i)s > 9 \ \text{Residences and 49 Employees} = 1; \qquad (2)$$

0 otherwise]/*S*

[min = 0; max = 1]

## Concentration (three alternatives)

- Very high density grids (with respect to housing units or employees) as a percentage of all grids with developable land within the UA. Very high density grids are grids that are two standard deviations or more above the mean of the density of all grids in the 100 largest UAs (or in a sample of the 100 largest UAs) or,

- The coefficient of variation.

$$\text{COV}(i) \ u = (\overset{M}{\underset{m=1}{\Sigma}} [D(i)m - D(i)u]^2/M)^{1/2} \ / \ [\overset{M}{\underset{m=1}{\Sigma}} D(i)m/M] \qquad (3)$$

or,

- Delta index.

$$\text{DELTA}(i)u = (1/2) \ \overset{M}{\underset{m=1}{\Sigma}} \ \big| \ [T(i)m/T(i)u] - [Am/Au] \ \big| \qquad (4)$$

## Clustering

$$\text{CLUS}(i)u = [\overset{M}{\underset{m=1}{\Sigma}} \ (\overset{4}{\underset{s=1}{\Sigma}} [D(i)s - D(i)m]^2/4)^{1/2}/M] \ / \ [\overset{M}{\underset{m=1}{\Sigma}} D(i)m/M] \qquad (5)$$

## Centrality (two alternative measures)

- The average distance of a land use (e.g., housing units) from the CBD.

$$\text{CBDDIST} = T(i)u(A^{1/2})/\overset{M}{\underset{m=1}{\Sigma}}F(k,m)\,T(i)m \tag{6}$$

- The centralization index:

$$\text{CEN}(j)u = \overset{H}{\underset{h=1}{\Sigma}}[T(j)h-1][Ah] - \overset{H}{\underset{h=1}{\Sigma}}[T(j)h][Ah-1] \tag{7}$$

## Nuclearity

Nuclearity involves the identification of nodes or nuclei. The identification proceeds in the following steps:

1. Identify the highest density (in terms of both housing units and, separately, employees) per one-mile-square grid in the UA.

2. Add all adjacent grids within one standard deviation of the density of this highest-density grid to the node, as well as nodes adjacent to the added nodes, provided they are within one standard deviation of the highest-density grid. The result is the central node, $c$.

3. Recalculate the density of the newly combined highest-density nucleus $c$ (per #2)

4. Consider all other one-mile-square grids in the UA that are within one standard deviation of the recalculated density (per #3) as separate nuclei, $n$, provided that they are not immediately adjacent to an existing nucleus.

5. Add any grids adjacent to any nucleus identified in #4 that are within one standard deviation of the recalculated highest-density nucleus $c$ (per #3) to the nucleus.

Two alternative measures can be defined now:

$$\text{NODES} = c + \Sigma n = c + N \tag{8}$$

$$\text{MONONUCLEAR} = T(i)c/[T(i)c + \overset{N}{\underset{n=1}{\Sigma}}T(i)n] \tag{9}$$

## Mixed uses

$$\text{MXU } (j \text{ to } i) = \sum_{m=1}^{M} (D(i)m \times [D(j)m/T(j)u])/D(i)u \tag{10}$$

[min = 0; max = max $D(i)m$ observed in any area occupied by $j$]

## Proximity

The average distance between any two randomly chosen observations of different land uses $i$ and $j$ can be expressed as

$$\text{DIST}(i, j)u = \sum_{m=1}^{M} \sum_{k=1}^{M} F(i, j)mk \ [T(j)k/T(j)u](T(i)m/T(i)u) \tag{11}$$

[min = 1 mile; max = unlimited]

Analogously, the average distance between any two randomly chosen observations of the same land use $j$ in the UA can be expressed as

$$\text{DIST}(j, j)u = \sum_{m=1}^{M} \sum_{k=1}^{M} F(j, j)mk \ [T(j)k \times T(j)m]/(T(j)u)^2 \tag{12}$$

It makes sense to standardize these distance measures, inasmuch as bigger UAs will tautologically have greater average distances between any pair of land uses. For this standardization, we compute the average distance between centroids of the $M$ medium-scale grid areas:

$$\text{DIST}u = \sum_{m=1}^{M} \sum_{k=1}^{M} Fmk/M \tag{13}$$

[min = 1 mile; max = unlimited]

From the above terms, we can express three alternative measures of proximity: intrause, interuse, and (weighted) average across uses:

$$\text{PROX}(j) = [\text{DIST}u/\text{DIST}(j, j)] - 1 \tag{14}$$

$$\text{PROX}(ij) = [\text{DIST}u/\text{DIST}(i, j)] - 1$$

$$\text{PROX}(u) = (\text{DIST}u \ [T(i)u + T(j)u])/(T(i)u[\text{DIST}(i, i)] + T(j)u[\text{DIST}(j, j)] \ ) - 1$$

All three versions of proximity indices have the mathematical property that they will equal zero if observations of the given land use (or average of land uses) are separated, on average, as are all parcels of land in the UA. Positive values of these indices signify that observations of the given use are more proximate, on average, than are all parcels to each other; the maximum value is undefined since the intra- or interuse distance may be very small compared with all parcels. Conversely, negative values of these indices denote use separations greater than those among parcels; the indices approach but cannot equal –1 as a minimum.

*Appendix B*

*Grid formulation methodology*

The data source for these calculations was U.S. Census Bureau 1995 TIGER/Line-based files from Environmental Systems Research Institute, Inc. (ESRI). MapInfo Professional v. 5.5 and ArcView v. 3.2 were the types of Geographic Information Systems software used.

## Methodological summary

Data for all 13 UAs (UA boundaries and census blocks for all counties comprising them) were acquired from ESRI and converted to MapInfo format for analysis. After importation, only block-level geography within the UAs studied was kept. Block-level housing unit data was then "joined" to the geography.

## Grid cell creation

One set each of one-mile-square and one-half-mile-square cells were then created from a rectangular grid boundary drawn around each UA to encompass it in its entirety. Grid tables were then created on the basis of these bounding rectangles.

## UA calculation

Once grid cells were created, they were assigned a value between 0 and 1 based on the percentage of their area that fell within the UA being studied; for example, if a cell fell wholly within the UA boundary, it was assigned a value of 1. Those entirely outside the area were assigned a value of 0. Those straddling the border were assigned the geographical proportion that fell within the area.

## Housing unit calculation

The methodology for this calculation was somewhat different in that block-level geography was used in the one-mile and one-half-mile cell calculations. However, the cell file geography remained unaltered. The number of housing units was assigned on the basis of the proportionate sum of that portion of the blocks that partially or wholly fell within the boundaries of the individual cells. For example, if it was geographically determined that a particular one-mile cell contained all or part of four blocks that crossed its borders, then only the geographically based proportion of housing units of each block that fell within that cell were summed to it.

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