# A Housing-Unit-Level Approach to Characterizing Residential Sprawl

**John Hasse and Richard G. Lathrop**

## Abstract

*Five spatial metrics are developed at the housing-unit level for analyzing spatial patterns of urban growth in order to better identify the characteristics and qualities of urban sprawl. A multi-temporal land-use/land-cover dataset for Hunterdon County, New Jersey is utilized to measure new housing units developed between Time 1 (1986) and Time 2 (1995) for five traits defined as "sprawl" in the planning and policy literature: (1) density, (2) leapfrog, (3) segregated land use, (4) accessibility, and (5) highway strip. The resulting housing-unit sprawl indicator measurements are summarized by municipality to provide a "sprawl report card." The analysis provides a new direction in sprawl research that addresses sprawl at the atomic level, captures the temporal nature of urban growth, and provides measures that are potentially useful to planners addressing sprawl.*

## Introduction

The phenomenon of sprawling urban development is one of the major forces driving land-use/land-cover change in the United States. Urban sprawl has been characterized within the planning and policy literature and land management field as a distinct form of dispersed and inefficient urban growth, haphazard in configuration, and highly reliant on the automobile (Florida Division of Community Planning, 1993; Ewing, 1997; Downs, 1998; Burchell and Shad, 1999; Sierra Club, 1999; Vermont Forum on Sprawl, 1999). The costs and negative externalities of urban sprawl have been widely documented (Duncan, 1989; Frank, 1989; Kunstler, 1993; Burchell *et al.*, 1998; Kahn, 2000; Freeman, 2001). In response to the negative aspects of sprawl, a number of remedies have been proposed, including the "new urbanism" of planning (Duany and Plater-Zyberk, 1991; Calthorpe, 1993; Nelessen, 1993) and what others have labeled "smart growth" (Danielsen *et al.,* 1999) (Smart Growth Network, http://www.smartgrowth.org/about/default.asp, last accessed 19 May 2003). Others have defended the benefits incurred from sprawl-style development and argue that the American patterns of suburbanization are the result of free market forces, consumer choice, and a reflection of the democratic system of land governance (Gordon and Richardson, 1997; Easterbrook, 1999; Carliner, 1999).

While substantial research and academic discourse has addressed many of the socioeconomic issues related to sprawl on a metropolitan-wide basis, far less research has focused on developing concrete methodologies able to identify and characterize sprawl. While we all "know it, when we see it," there is no presently accepted standard to distinguish whether new residential development tracts are actually sprawling in their physical configuration and location. Definitions of sprawl in the literature run the gamut from a very specific manifestation of problematic urban growth (Benfield *et al.,* 1999) to any new urban development at all (Fodor, 1999). With such loose usage, the term "urban sprawl" is at risk of becoming hackneyed or outright meaningless. We address this issue by developing several standardized metrics for analyzing spatial patterns of urban growth to better identify the spatial characteristics and qualities of urban sprawl.

### Defining Sprawl

Characterizing *urban sprawl* using spatial measures requires a concise definition of what exactly constitutes sprawling urban spatial patterns. Burchell and Shad (1998; 1999) define sprawl as "low density residential and nonresidential intrusions into rural and undeveloped areas, and with less certainty as leapfrog, segregated, and land consuming in its typical form." Ewing (1997) offers a summary of 17 references to sprawl in the literature as being characterized by "low density development, strip development, and/or scattered or leapfrog development." Ewing suggests that the lack of non-automobile access is also a major indicator of sprawl. Downs (1998) and the Florida Division of Community Planning (1993) provide succinct descriptions of sprawl (Table 1).

Other researchers are beginning to explicitly define sprawl in geographical terms of measurable spatial patterns. Torrens and Alberti (2000) are developing an empirical landscape approach to sprawl measurement that focuses on the characteristics of density, scatter, the built environment, and accessibility. Galster *et al.* (2001) defined sprawl as "a pattern of land use in an urbanized area that exhibits low levels of some combination of eight distinct dimensions: *density*, *continuity*, *concentration*, *compactness*, *centrality*, *nuclearity*, *diversity*, and *proximity.*" Operationally, several of these dimensions of sprawl have been measured for selected metropolitan areas at a comparatively coarse spatial resolution using U.S. census data gridded into one-half-mile cells (Galster *et al.*, 2001). More recently, this work has been expanded to implement a larger set of spatial measures for a greater number of metropolitan areas (El Nasser and Overberg, 2001; Ewing *et al.*, 2002). While these coarser scale approaches have been especially useful for inter-metropolitan comparison at a nationwide scale, methods that employ a finer level of resolution are also needed to further illuminate intra-metropolitan patterns of urban growth.

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J. Hasse is with the Department of Geography and Anthropology, Rowan University, 201 Mullica Hill Road, Glassboro, NJ 08028 (hasse@rowan.edu).

R.G. Lathrop is with the Grant F. Walton Center for Remote Sensing and Spatial Analysis, Natural Resources & Environmental Sciences Building, Cook College, Rutgers University, 14 College Farm Road, New Brunswick, NJ 08901-8551 (lathrop@crssa.rutgers.edu).

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TABLE 1. CHARACTERISTICS OF SPRAWL

| Downs (1998) | Florida Division of Community Planning (1993) |
|---|---|
| Unlimited outward extension of development | Allows large areas of low-density or single-use development |
| low-density residential and commercial settlements | Allows leapfrog development |
| Leapfrog development | Allows radial, strip, or ribbon development |
| Fragmentation of powers over land use among many smaller localities | Fails to protect natural resources |
| Heavy reliance on private automobiles as the primary transportation mode | Fails to protect agricultural land |
| No centralized planning or control of land uses | Fails to maximize use of public facilities |
| Widespread commercial strip development | Allows land use patterns that inflate facility costs |
| Significant fiscal disparities among localities | Fails to clearly separate urban and rural uses |
| Segregation of land use types into different zones | Discourages infill development or redevelopment |
| Reliance on a "trickle-down" or filtering process to provide housing to low-income households | Fails to encourage a functional mix of uses |
|  | Results in poor accessibility among related land uses |
|  | Results in loss of significant amounts of functional open space |

The burgeoning spatial analysis approach to sprawl is providing a more rigorous and objective analytical foundation for academic research. However, this work needs to be further developed in three significant capacities: (1) the temporal nature of the sprawl process; (2) the ability to characterize urban growth at it's atomic level, namely (for residential development) the housing unit; and (3) the utility of sprawl measurement to the planning process. Many of the metrics developed thus far are static in nature, missing the dynamic component of sprawl. Sprawl metrics are needed that focus on characteristics of urban growth rather than a static snapshot of overall urban structure. Secondly, sprawl and smart growth analysis can be conducted at multiple scales and geographical extents. Analytical methods that may be appropriate at a census tract scale will be markedly different from analytical methods for a planning zone or metropolitan region. The atomization of urban growth analysis to the housing unit allows the easy rescaling and rezoning of analysis across varying scales and extents. Lastly, metrics are needed that can be realistically utilized within the trenches of the planning process. Sprawl metrics developed thus far present little cogent information on what is specifically problematic about a particular tract of development or what land-use measures might effectively address the problematic characteristics of a new development tract.

## Developing Housing-Unit-Level Sprawl Measures

These various definitions attempt to describe sprawl as a specific form of urban development with inherent spatial qualities and characteristics that distinguish sprawl from urban growth in general and by implication suggest that there must also be patterns of urban growth that exhibit spatial characteristics which are the antithesis of sprawl. This "anti sprawl" development pattern is sometimes labeled *smart growth* (Danielsen *et al.*, 1999) (Smart Growth Network, http://www.smartgrowth.org/about/default.asp, last accessed 19 May 2003). While the term *smart growth* represents more than simple landscape configuration, we utilize the term in this analysis to represent the opposite of sprawling characteristics. In reality, any given development tract will exhibit multiple spatial characteristics on a continuum between the most extreme sprawl and the most ideal smart growth. Furthermore, any given development tract may simultaneously embody some characteristics of sprawl and some other characteristics of smart growth.

Our approach to sprawl measurement focuses on the inefficient characteristics of sprawling development and the per capita impact imparted by particular forms of development. Because the actual population of any given residential unit is not publicly available information, the analysis utilized housing units as a proxy for population. A reasonable estimate of the population for any given tract of development could be calculated by simply multiplying the number of units within a development tract by the average number of residents per household. Therefore, because the number of housing units within a patch of new development could be delineated within a GIS, it is used as a proxy for population throughout the analysis.

The location of housing units within a development tract can be easily identified on an orthophoto. However, on-screen demarcation of each new housing unit is impractical at a county-level basis. Our implementation of housing-unit-level sprawl measures relies on a digital land-use/land-cover (LU/LC) change map product that includes LU/LC at two points in time. Polygons of new residential development (i.e., new housing tracts) that occurred between Time 1 (1986) and Time 2 (1995/97) were extracted from the land-use/land-cover dataset.

An automated demarcation of housing units was developed by intersecting polygons of new residential development patches with a countywide 2000 digital parcel coverage (see Figure 1). Because each property parcel in a rural county such as Hunterdon is generally restricted to only one single-housing unit (with the exception of certain special cases such as condominiums), the number of subdivided parcels within a patch accurately represented the number of housing units. The subdivided polygons were converted to polygon centroids. A "point-in-polygon" method was utilized to sum the number of parcel centroids within each original development patches to provide an estimate of the number of housing units contained in each new urban patch. Figure 2 depicts an example of the automated housing centroid delineation.

Once the new housing-unit centriods were estimated, spatial measurements were then employed. Five of the most significant spatial characteristics for distinguishing sprawl versus smart growth were developed into spatial metrics. Measurements included *density, leapfrog, segregated land use, community node inaccessibility,* and *highway strip.* Calculations were made for each new housing unit and then summarized by municipal boundaries to provide a "sprawl report card" for recent growth in each locality.

### Urban Density

The urban density indicator provides a measure of the amount of land area occupied by each housing unit. In order to facilitate scaling of housing unit measures to other geographic units (in our pilot study we are scaling to the municipality), the housing centroid points were also assigned a municipal name field. The average municipal housing unit value for urban density by municipality ($UD_{mun}$) was calculated by summing the land areas for each new housing unit and dividing by the total number of units to occur within each

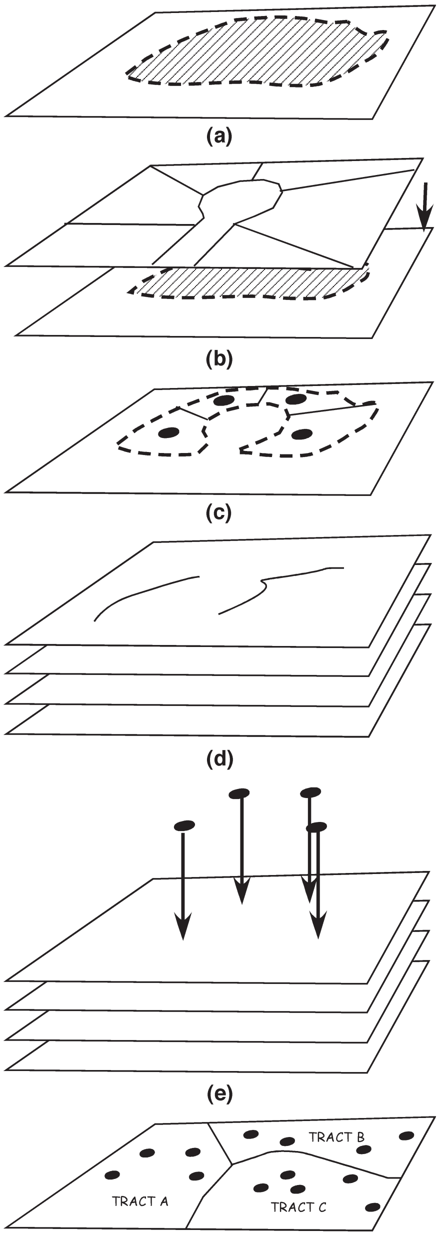

Figure 1. Steps in calculating housing-unit-level sprawl analysis. (a) Delineation of new urbanization (image classification or heads-up digitizing). (b) Intersection of new development patches with digital parcel map. (c) Polygon centroids estimate location of new housing units. (d) Generation of various sprawl parameters (example: *density, leapfrog, segregated land use, highway strip,* and *community node inaccessibility*). (e) Assignment of various sprawl parameters to housing unit point theme. (f) Summary of individual housing-unit metric values by regions of interest such as census tracts or municipalities.

municipality as depicted in Equation 1. Lower density indicates a sprawling signature for the density measure.

$$UD_{mun} = \left(\sum DA_{unit}\right) \Big/ N_{mun} \tag{1}$$

where $UD_{mun}$ is the urban density index for new urban growth within a municipality, $DA_{unit}$ is the developed area of each unit, and $N_{mun}$ is the number of new residential units in a given municipality.

Figure 2. Housing Centroid Automation. This image depicts an orthophoto of one newly developed housing tract. The thick lines delineate the "patches" of new urban growth as classified by the land-use/land-cover dataset. The thin lines delineate the property parcel lines. The target symbol denotes the automated centroid location estimated for each new housing unit. Sprawl measurements are calculated for each housing-unit centroid.

### Leapfrog

Patches of urban growth that occur at a significant distance from previously existing settlements are considered *leapfrog*. The leapfrog indicator was calculated by measuring the distance from the location of each new housing unit (at Time 2) to previously settled areas (at Time 1). The previous settlements were delineated as patches of urban land use existing in Time 1 that corresponded to designated place names on a USGS quadrangle map or existing patches larger than 50 acres (20 hectares). This filtered out smaller non-named patches of Time 1 urban areas that had already leapfrogged from settled areas. A straight-line distance grid was generated from these "previously settled" patches and the value was assigned to each new housing unit. The housing unit leapfrog value was scaled to the municipal leapfrog index ($LF_{mun}$) by summarizing the leapfrog field value of the housing unit point layer by municipality as depicted in Equation 2. New growth that occurs at large leapfrog distances is considered sprawling.

$$LF_{mun} = \left(\sum Dlf_{unit}\right) \Big/ N_{mun} \tag{2}$$

where $LF_{mun}$ is the leapfrog index for new urban patches within a municipality, $Dlf_{unit}$ is the leapfrog distance for each new unit, and $N_{mun}$ is the number of new residential units in a given municipality.

### Segregated Land Use

A third characterization of sprawl is segregated land use. Single-use zoning results in large regions of strictly segregated residential, commercial, or industrial land uses. Because mixed land-use areas may look segregated on a micro level, the definition of segregated land use employed here is new housing units beyond reasonable walking distance to multiple other types of urban land uses. New residential units within a 1,500 foot (450 meters) pedestrian distance (the typical distance a pedestrian will walk in 10 minutes (Nelessen, 1993)) to multiple other types of urban land uses are considered *mixed* while housing units with only a single land use within the pedestrian distance are considered *segregated*.

The segregated land-use metric was calculated by converting the vector-based "urban" land-use/land-cover data layer to a grid. The data set included 18 different classes of *urban* land use, some of which were recoded to better reflect the segregated land-use analysis. The *mixed-use* urban category of the dataset was recoded to a value of 3 (i.e., considered three different urban land uses) to compensate for the fact that, although it is classified as a single category, it should be considered already mixed. The three different categories of "single unit residential" (*rural single unit, single unit low density*, and *single unit medium density*) delineated in the dataset were recoded to a single class labeled "single unit residential" to compensate for the tendency of multiple single-unit categories to skew the results toward a higher land-use mixture than warranted. A *neighborhood variety* calculation was performed on the gridded urban land use utilizing a radius of 1,500 feet (450 meters) to represent the pedestrian distance. This produced a grid surface where every cell was enumerated according to the variety or mixture of different urban land use categories within the search radius.

Because the other sprawl indicator measures produce output in which higher values indicate higher sprawl, the *mixed land use* surface grid was inverted to a *segregated land use* value where a higher value represents a greater indication of the non-mixed nature of sprawl. This was accomplished by subtracting the mixed-use grid from a constant grid with a value equal to 1 plus the most mixed grid cell occurrence (in our pilot study, the maximum mixed land-use occurrence within the pedestrian distance was seven). The municipal-level segregated land-use index ($SL_{mun}$) was calculated by averaging the segregated land-use value of each new housing unit by municipality as depicted in Equation 3. New urban growth that exhibits a higher proportion of segregated land use is considered more sprawling than a mixed land-use pattern for this measure.

$$SL_{mun} = \left(\sum Seg_{unit}\right) \Big/ N_{mun} \tag{3}$$

where $SL_{mun}$ is the segregated land-use indicator by municipality; $Seg_{unit}$ is $X$ minus the number of different developed land uses within 1,500 ft (450 m) of a given housing unit, in which $X$ is one plus the maximum land-use mix in a given dataset. (note: the baseline land-use mix will vary by dataset), and $N_{mun}$ is the number of new residential units in a given municipality.

### Highway Strip

The highway strip development component of sprawl is usually typified by fast food restaurants and retail strip malls but can also include single-family housing units lining rural highways. In our present analysis, we are only focusing on residential growth. As developed, the highway strip index is a binary measure. Residential units are designated highway strip if they occur along rural highways outside of town centers and the surrounding urban growth boundaries. New housing units within the delineated rural highway buffer are considered sprawling for this measure.

For this study, the rural highways were delineated from the dataset as all non-local roads (i.e., county-level highway or greater) outside of designated centers of the New Jersey State Plan. The buffer was set at 300 ft (100 m), a common depth for a 1-acre (0.4-ha) housing lot. Housing units that fell within the buffer were coded to 1 and units outside the buffer were coded to zero. The municipal-level highway strip index ($HS_{mun}$) was calculated by summing the number of new residential units that occurred within the highway buffer and then normalizing by the total number of new units that were developed within the municipality as depicted in Equation 4. This provided, in essence, a probability measure of highway strip occurrence for each municipality. Municipalities that experienced a higher ratio of residential highway strip development were considered more sprawling for this measure than were municipalities with lower ratios.

$$HS_{mun} = \left(\sum HB_{unit}\right) \Big/ N_{mun} \tag{4}$$

where $HS_{mun}$ is the highway strip indicator by municipality, $HB_{unit}$ is the residential unit within highway buffer, and $N_{mun}$ is the number of new residential units in a given municipality.

### Community Node Inaccessibility

The community node inaccessibility index measures the average distance of new housing units to a set of nearest community nodes. The centers chosen in this pilot analysis included schools, libraries, post offices, municipal halls, fire and ambulance buildings, and grocery stores. The centers were chosen to reflect likely destinations for residents within a community as well as the availability of data for center locations. Each node was identified in the countywide digital parcel map utilizing the owner information as well as interpretation of digital orthophotos and hardcopy county maps.

New housing units were analyzed for their road network distance to the set of community nodes utilizing a cost/distance calculation over a combined gridded roads and urban mask. Road network distances were generated for each individual community node type to the new housing units. The individual community node distance values were averaged into a single community node distance value for each housing unit. The municipal-level community node inaccessibility index ($CNI_{mun}$) was calculated by summarizing the new housing unit community node distance values by municipality as depicted in Equation 5. Sprawling land-use patterns have significantly higher average distances between new housing units and the selected community nodes.

$$CNI_{mun} = \left(\sum Dcn_{unit}\right) \Big/ N_{mun} \tag{5}$$

where $CNI_{mun}$ is the community node inaccessibility index by municipality, $Dcn_{unit}$ is the average distance of new residential unit to the set of community nodes, and $N_{mun}$ is the number of new residential units in a given municipality.

### Normalizing Municipal Sprawl Indicator Measures

Each of the five individual sprawl measures reflects a particular geospatial characteristic of urban growth and provides useful analytical information. However, the measures are not standardized but reflect an appropriate measurement unit for each particular trait. For example, some measurements such as *leapfrog* are linear distances, some such as *density* are areal measures, and yet others such as *segregated land use* are in numbers of land uses. The diversity and range between these measurement units precludes quantitative comparison between measures. Normalization of the measures through percentile rank results in index values that can be cross-compared. Once the individual sprawl measures were normalized to percentage ranks, they were summed together to produce a single cumulative summary measure of sprawl, or what we characterize as a *Meta-Sprawl Indicator* for each municipality.

## A Case Study: Hunterdon County, New Jersey

In order to develop and operationalize an automated sprawl calculation, a municipal-level sprawl analysis was performed on Hunterdon County, New Jersey. This once rural county has experienced significant suburbanization in recent decades and

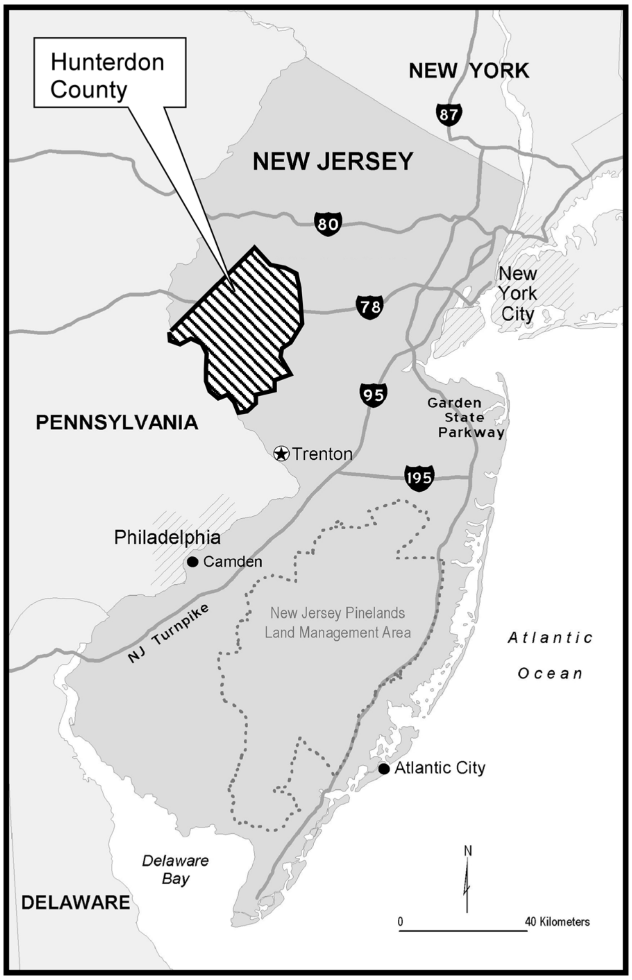

Figure 3. Hunterdon County, New Jersey.

was chosen as the study area due to many qualities that exemplify the problems of sprawling urban growth along the rural-urban fringe. Hunterdon County is located in a traditionally agricultural region of western New Jersey, approximately 50 miles (80 km) west of New York City and 50 miles (80 km) north of Philadelphia (Figure 3). This puts the entire county within "acceptable" commuting distance to these major metropolitan areas.

Hunterdon County's demographic setting also makes for an interesting analysis of suburbanization because it has experienced significant population growth over the last few decades, rising from 69,718 in 1970 to 121,989 by 2000, a 75.2 percent increase in population (U.S. Census Bureau, 2001). Although the county's population is relatively low when compared with other New Jersey suburban counties, Hunterdon's rate of growth is outstripping the state as a whole. The increase in county population from 1990 to 2000 was 13.1 percent compared to the 8.6 percent statewide growth. These geographic factors and growth pressures make the county an ideal case study for measuring geospatial patterns of urban sprawl on the rural fringe.

### Data

The *housing unit* approach to urban growth analysis requires extensive geospatial data. Detailed land-use/land-cover change data is a critical input. The New Jersey Department of Environmental Protection (NJDEP) contracted the production of the digital LU/LC data for the entire state utilizing multi-date digital ortho-photographic imagery (Thornton *et al.*, 2001). This statewide data set contains LU/LC information from 1986 (Time 1) and 1995/1997 (Time 2) as well as estimates of impervious surface coverage for each land-use map unit (i.e., polygon). The LU/LC dataset includes over 50 categories of classes utilizing a modified Anderson *et al.* (1976) classification system. The New Jersey dataset was produced from an original 1986 land-use/land-cover dataset delineated from 1986 orthophotoquads. The dataset was updated to 1995/97 and enhanced in spatial accuracy through "heads-up" on-screen digitizing and editing techniques. The 1995/97 digital imagery were color-infrared USGS digital orthophoto quarter quads (DOQQs) (1:12,000 scale) with a 1-meter grid cell resolution. Data were delineated to a spatial accuracy of ±60 feet (±18 m) in the original 1986 data and further adjusted in the 1995/97 update. A minimum mapping unit of 1 acre (0.4 ha) was utilized for delineating features as well as a 60-foot (18-m) minimum width for mapping linear features.

A second vital database utilized in the analysis included the Hunterdon County 2000 digital parcel map. This coverage provided parcel boundaries and attribute information for Hunterdon's 50,000+ parcels. The parcel mapping was produced in-house by the Hunterdon County Planning Department using the GPS road centerlines as the spatial reference for map conflation.

### Results

#### *Countywide Analysis*

The automated analysis resulted in the delineation of 9,339 new residential units developed in Hunterdon County between 1986 and 1995. The five individual sprawl measures were calculated for the housing unit centroid layer. The countywide summary statistics provided in Table 2 present a measure of the "average" characteristics of sprawl for all new residential growth within Hunterdon County during the period of analysis. The sprawl measures indicate an average development density of 0.835 acres (0.338 hectares) developed for every unit; an average leapfrog distance of 2,035 feet (620.3 meters); a segregated land-use index value of 5.01, signifying an average of 2.99 different land uses within 1500 feet (450 meters) of each new residence; and important community nodes were located an average of 13,418 feet (4,089.8 meters) from each residential unit, and 5.8 housing units out of 100 were classified as highway strip.

A cross-correlation analysis (Table 3) demonstrates the degree to which each sprawl measure is correlated to each other. The results show that the five sprawl indices are substantially orthogonal, because no two measures are highly correlated. The *community node inaccessibility* measure stands as the sprawl indicator index most highly correlated to multiple other measures, including *leapfrog* and *segregated land use*. This is not unexpected because the other site-specific land-use patterns inherent to a new residential unit

TABLE 2. COUNTY-LEVEL AVERAGE SPRAWL STATISTICS FOR ALL NEW HOUSING UNITS BUILT IN HUNTERDON COUNTY BETWEEN 1986 AND 1995. $N = 9339$

| | $UD_{mun}$ | $LF_{mun}$ | $SL_{mun}$ | $CNI_{mun}$ | $HS_{mun}$ |
|---|---|---|---|---|---|
| Mean | 0.835 | 2035 | 5.01 | 13418 | 0.058 |
| Stdev | 0.848 | 2364 | 1.50 | 5573 | 0.234 |
| Min | 0.001 | 0 | 1.00 | 2334 | 0.000 |
| Max | 15.643 | 17452 | 7.00 | 36201 | 1.000 |

[$UD_{mun}$ = *urban density* in acres per unit]
[$LF_{mun}$ = *leap frog* distance in feet]
[$SL_{mun}$ = *segregated land use* in number of different urban land uses less than the study area maximum]
[$CNI_{mun}$ = *community node inaccessibility* distance in feet]
[$HS_{mun}$ = *highway strip* in ratio of new units along rural highways]

TABLE 3. SPRAWL INDICATOR CROSS-CORRELATION MATRIX FOR ALL NEW RESIDENTIAL UNITS BUILT BETWEEN 1986 AND 1997. $N = 9339$

| | $UD_{mun}$ | $LF_{mun}$ | $SL_{mun}$ | $CNI_{mun}$ | $HS_{mun}$ |
|---|---|---|---|---|---|
| $UD_{mun}$ | 1.000 | | | | |
| $LF_{mun}$ | 0.276 | 1.000 | | | |
| $SL_{mun}$ | 0.525 | 0.474 | 1.000 | | |
| $CNI_{mun}$ | 0.425 | 0.653 | 0.641 | 1.000 | |
| $HS_{mun}$ | −0.011 | 0.074 | 0.001 | 0.041 | 1.000 |

[$UD_{mun}$ = *urban density*]
[$LF_{mun}$ = *leap frog*]
[$SL_{mun}$ = *segregated land use*]
[$CNI_{mun}$ = *community node inaccessibility*]
[$HS_{mun}$ = *highway strip*]

will be linked to the accessibility of community nodes. The multiple correlation of the *community node inaccessibility* index suggests that a calculation of this index alone may be a useful proxy for many other characteristics of sprawl.

### *Municipal Level Analysis*

Table 4 presents the municipal results expressed as their average index value as well as in standard deviations from the norm (italicized type) for each measure. Municipalities that exhibited sprawl measurements more sprawling than the countywide average have positive standard deviations whereas negative standard deviation values indicate characteristics less sprawling than the county average. The range of the municipal-level sprawl measures demonstrate the diverse nature of residential growth from municipality to municipality. Some localities such as East Amwell Township exhibit growth patterns that are substantially more sprawling than the county average for all sprawl measures. Others such as Lebanon Borough are substantially less sprawling across all sprawl measures. Still other municipalities demonstrate a mixture of characteristics with some values more sprawling than average and others less sprawling than average.

Particularly interesting are Raritan and Readington Townships which, combined, accounted for 47.7 percent of the 9,339 residential units built countywide. These towns exemplify the type of explosive recent growth often perceived as sprawl, but examination of their sprawl measures finds them less sprawling than the county average for most sprawl variables. An equally interesting characteristic (Table 4) is the number of housing units developed within each municipality for the period of analysis. Raritan, Readington, and Clinton Townships gained the most units. Many of the smaller towns and boroughs exhibited relatively fewer new units of residential growth.

The average measures for each sprawl indicator are mapped in Z-scores (standard deviations) from the county mean by municipality in Plates 1a through 1e. The maps depict the municipal average measures for each index where shades of red indicate sprawling characteristics for towns greater than the county average and shades of blue indicate sprawling characteristics lower than average. In order to depict the actual spatial pattern of growth that occurred in each of the municipalities, the choropleth maps are overlaid with a delineation of 1986 urban (i.e., Time 1) in gray and new residential housing growth (Time 2) in yellow. The maps demonstrate the geographical variation of each measure from municipality to municipality. The spatial patterns of the individual sprawl measures are strikingly dissimilar, supporting the conclusion of orthogonality demonstrated by the cross correlation analysis (Table 3). Plate 1f maps the *meta-sprawl* indicator. Table 5 contains the normalized meta-sprawl values by municipality, ranked in descending order, placing the most sprawling municipality at the top.

## Discussion

The case study demonstrates that the sprawl indicator measures provide a robust set of tools for analyzing spatial patterns of urbanization. Immediately evident in the results are the differences between municipality types. New Jersey has four categories of municipal governments: (1) city, (2) town, (3) borough, and (4) township. Cities, towns, and boroughs are the older communities, usually incorporated as settlements and initially settled in many cases in the 19th century or earlier. Townships, on the other hand, were traditionally unincorporated rural jurisdictions with originally sparse settlement patterns. However, more recently townships have become the hotbeds for suburban growth, accounting for 93.4 percent of all new residential units built in Hunterdon County during the 1986 through 1995 study period. Much of the growth in townships exhibit elevated sprawl indicator values compared to the boroughs, indicating the propensity for townships to sprawl.

It is significant to note that there is considerable difference in size between the different types of municipalities in New Jersey. The size of boroughs, cities, and towns taken together in Hunterdon County is on average 800 acres (320 ha), whereas the average township is 17,800 acres (7200 ha) in size. Population growth was marginal and in some cases negative in Hunterdon cities, towns, and boroughs, averaging 6.2 percent as a group between 1986 and 1995 versus an average 13.7 percent population growth for the townships. Average urban land growth for the same years was 8.4 percent for towns, cities, and boroughs versus 30.4 percent for townships. Clearly, if growth of low urban density were solely used as a sprawl indicator, townships are epitomizing low-density urban growth.

While the meta-sprawl index provides a convenient single numeric value of sprawl for comparing municipalities, it should be not be given too much emphasis. In many ways the meta-sprawl index loses much of the valuable information provided by the individual sprawl indicator measures utilized as a set. Sprawl is more complex than can be adequately captured by a single number. Nonetheless, the meta-sprawl index provides an approach to summarizing the overall sprawling nature of urban growth. While the meta-sprawl indicator and the individual metric municipal Z-scores provide for a useful inter-municipal comparison, these are empirically derived numbers unique to the Hunterdon County data set. As stated previously, these sprawl metrics represent a continuum of values, and as of yet we have not developed definitive thresholds as to what metric values constitute “sprawl” versus “smart growth.”

Care must be taken with any approach to measuring sprawl to ensure that the measures are not tautological. In other words, larger municipalities (i.e., townships) may be characterized as more sprawling for certain measures simply because they are large municipalities and have more available space to grow; therefore, the growth is more spread out, which appears as more sprawling in the sprawl indicator analysis. While this concern must be taken into consideration for size-sensitive measures such as the *leapfrog* and *community inaccessibility* indices, it is not an issue for the other sprawl indicators such as *density*, *highway strip*, and *segregated land use*. These characteristics of sprawling growth and their smart growth alternatives can occur just as readily in large municipal townships as in small municipal boroughs. Calculating the sprawl indicator measures on a per-housing-unit basis helps to diminish the effect of variations in municipal size because the measures can be re-summarized by subregions such as planning zones or census tracts.

Because sprawl is a function of the spatial pattern of individual housing units or commercial development in the context of surrounding land uses, our approach is powerful in

TABLE 4. MUNICIPAL-LEVEL SPRAWL INDICATOR MEASURES OF HUNTERDON COUNTY, NEW JERSEY. AVERAGE MEASURES ARE IN REGULAR TYPEFACE AND STANDARD DEVIATIONS FROM THE COUNTY AVERAGE ARE ITALICIZED IN THE GRAY BOX

| Municipality | Housing Units | $UD_{mun}$ | $LF_{mun}$ | $SL_{mun}$ | $CNI_{mun}$ | $HS_{mun}$ |
|---|---|---|---|---|---|---|
| Alexandria Twp | 448 | 1.32 | 3406 | 6 | 18976 | 0.078 |
| | | *0.572* | *0.580* | *0.660* | *0.997* | *0.085* |
| Bethlehem Twp | 287 | 1.1 | 3152 | 6 | 14578 | 0.122 |
| | | *0.313* | *0.473* | *0.660* | *0.208* | *0.274* |
| Bloomsbury Boro | 14 | 0.35 | 213 | 1.7 | 12113 | 0 |
| | | *−0.572* | *−0.771* | *−2.207* | *−0.234* | *−0.248* |
| Califon Boro | 18 | 0.57 | 576 | 3.8 | 9324 | 0.056 |
| | | *−0.313* | *−0.617* | *−0.807* | *−0.735* | *−0.009* |
| Clinton Town | 88 | 0.26 | 231 | 4.1 | 3392 | 0 |
| | | *−0.678* | *−0.763* | *−0.607* | *−1.799* | *−0.248* |
| Clinton Twp | 921 | 0.87 | 980 | 5 | 10894 | 0.089 |
| | | *0.041* | *−0.446* | *−0.007* | *−0.453* | *0.132* |
| Delaware Twp | 304 | 1.38 | 4381 | 6.3 | 17049 | 0.082 |
| | | *0.643* | *0.992* | *0.860* | *0.652* | *0.103* |
| East Amwell Twp | 224 | 1.25 | 5038 | 6.3 | 20856 | 0.147 |
| | | *0.489* | *1.270* | *0.860* | *1.335* | *0.380* |
| Flemington Boro | 8 | 0.39 | 80 | 2.9 | 3805 | 0 |
| | | *−0.525* | *−0.827* | *−1.407* | *−1.725* | *−0.248* |
| Franklin Twp | 171 | 1.48 | 3394 | 6.3 | 17188 | 0.035 |
| | | *0.761* | *0.575* | *0.860* | *0.676* | *−0.098* |
| Frenchtown Boro | 13 | 0.53 | 473 | 4.8 | 12922 | 0.308 |
| | | *−0.360* | *−0.661* | *−0.140* | *−0.089* | *1.068* |
| Glengardner Boro | 215 | 0.17 | 272 | 3.6 | 9076 | 0.005 |
| | | *−0.784* | *−0.746* | *−0.940* | *−0.779* | *−0.226* |
| Hampton Boro | 16 | 0.93 | 330 | 3.8 | 8929 | 0.125 |
| | | *0.112* | *−0.721* | *−0.807* | *−0.805* | *0.286* |
| High Bridge Boro | 17 | 0.49 | 164 | 4.8 | 8287 | 0.059 |
| | | *−0.407* | *−0.791* | *−0.140* | *−0.921* | *0.004* |
| Holland Twp | 372 | 0.95 | 1513 | 5.3 | 14269 | 0.048 |
| | | *0.136* | *−0.221* | *0.193* | *0.153* | *−0.043* |
| Kingwood Twp | 420 | 1.21 | 6648 | 6.4 | 22585 | 0.117 |
| | | *0.442* | *1.951* | *0.927* | *1.645* | *0.252* |
| Lambertville City | 110 | 0.15 | 249 | 4.1 | 4505 | 0 |
| | | *−0.808* | *−0.755* | *−0.607* | *−1.599* | *−0.248* |
| Lebanon Boro | 103 | 0.11 | 42 | 2.2 | 9115 | 0 |
| | | *−0.855* | *−0.843* | *−1.873* | *−0.772* | *−0.248* |
| Lebanon Twp | 350 | 1.17 | 3607 | 5.9 | 14066 | 0.031 |
| | | *0.395* | *0.665* | *0.593* | *0.116* | *−0.115* |
| Milford Boro | 11 | 0.59 | 224 | 5.8 | 9902 | 0 |
| | | *−0.289* | *−0.766* | *0.527* | *−0.631* | *−0.248* |
| Raritan Twp | 2383 | 0.63 | 1025 | 4.6 | 10318 | 0.042 |
| | | *−0.242* | *−0.427* | *−0.273* | *−0.556* | *−0.068* |
| Readington Twp | 2074 | 0.65 | 1621 | 4.4 | 14067 | 0.042 |
| | | *−0.218* | *−0.175* | *−0.407* | *0.116* | *−0.068* |
| Stockton Boro | 3 | 0.66 | 137 | 4.7 | 9748 | 0 |
| | | *−0.206* | *−0.803* | *−0.207* | *−0.659* | *−0.248* |
| Tewksbury Twp | 325 | 1.45 | 3162 | 6 | 17830 | 0.043 |
| | | *0.725* | *0.477* | *0.660* | *0.792* | *−0.064* |
| Union Twp | 327 | 0.85 | 1185 | 5.2 | 12908 | 0.061 |
| | | *0.018* | *−0.360* | *0.127* | *−0.092* | *0.013* |
| West Amwell Twp | 117 | 1.04 | 5642 | 6.2 | 14250 | 0.145 |
| | | *0.242* | *1.526* | *0.793* | *0.149* | *0.372* |

that it matches the scale of the metric with the scale of the phenomenon. Sprawl occurs one housing unit at a time, and even within a single development tract there may be considerable variability in the sprawling characteristics of individual homes. Measuring sprawl at the housing-unit level also facilitates investigation into other political and geographical factors that result in different manifestations of growth at the municipal level or for any geographical unit of interest such as neighborhood, census track, zoning region, congressional district, county, etc. The housing-unit-level sprawl indicator measures can simply be re-summarized at the region of interest and statistically analyzed against other socioeconomic data for the

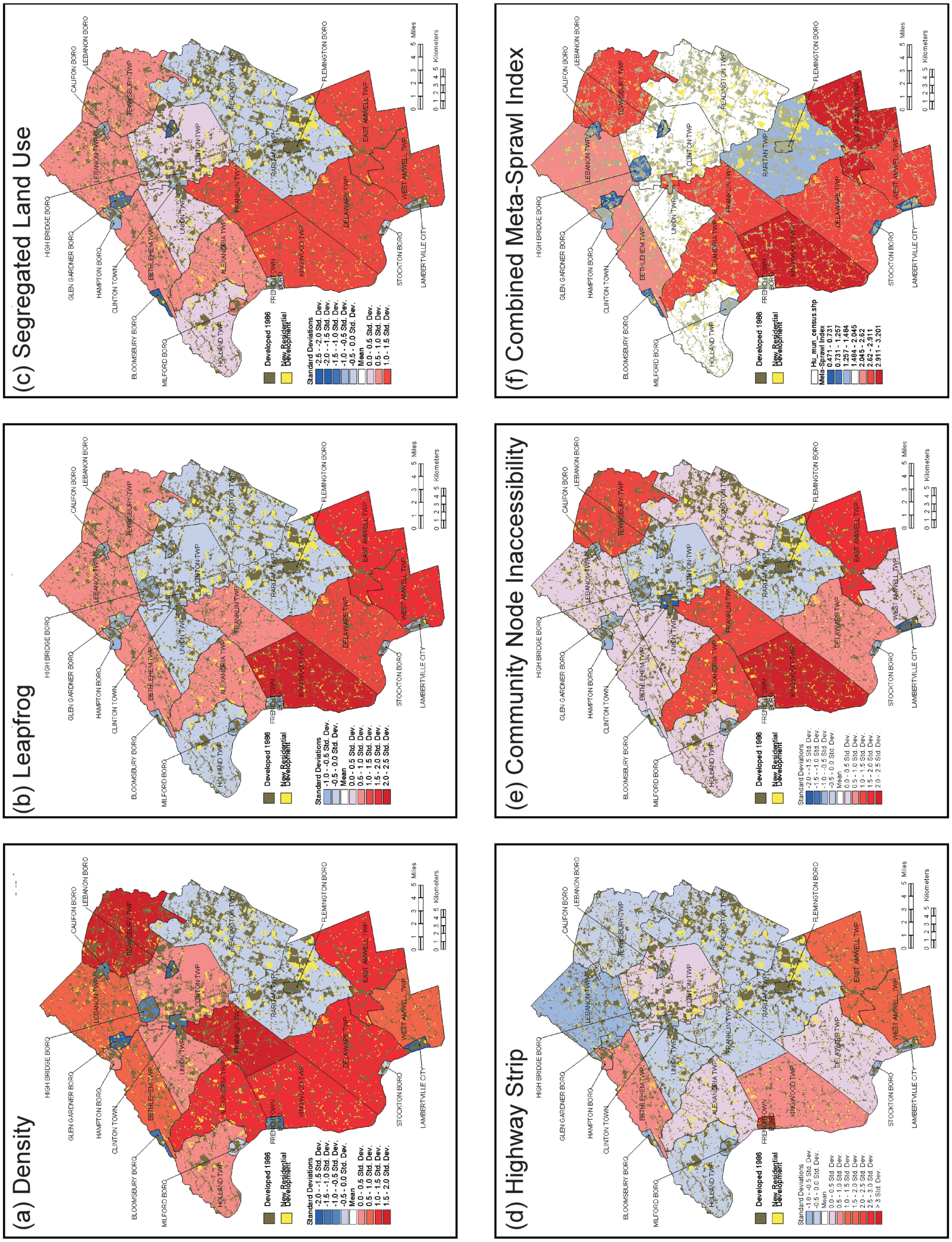

Plate 1. Municipal average sprawl measures (a-e) in Z-scores from the county average. Reds indicated greater than average values (i.e., more sprawling) whereas blues indicate less than average. Overlays of gray indicate areas of previous development and yellow indicate new residential growth. (f) The Metasprawl indicator combines the individual sprawl indices into a single indicator.

TABLE 5. NORMALIZED MUNICIPAL SPRAWL MEASURES RANKED BY METASPRAWL INDEX

| Municipality | $UD_{mun}$ | $LF_{mun}$ | $SL_{mun}$ | $CNI_{mun}$ | $HS_{mun}$ | Metasprawl Index |
|---|---|---|---|---|---|---|
| Kingwood Twp | 0.661 | 0.883 | 0.672 | 0.875 | 0.110 | 3.201 |
| East Amwell Twp | 0.680 | 0.784 | 0.627 | 0.821 | 0.139 | 3.051 |
| Delaware Twp | 0.708 | 0.794 | 0.628 | 0.703 | 0.078 | 2.911 |
| Alexandria Twp | 0.699 | 0.712 | 0.554 | 0.818 | 0.074 | 2.857 |
| Franklin Twp | 0.704 | 0.717 | 0.641 | 0.734 | 0.033 | 2.829 |
| Tewksbury Twp | 0.716 | 0.693 | 0.545 | 0.759 | 0.041 | 2.754 |
| West Amwell Twp | 0.616 | 0.781 | 0.619 | 0.542 | 0.137 | 2.695 |
| Bethlehem Twp | 0.637 | 0.704 | 0.575 | 0.589 | 0.115 | 2.620 |
| Lebanon Twp | 0.653 | 0.679 | 0.541 | 0.537 | 0.030 | 2.440 |
| Holland Twp | 0.552 | 0.460 | 0.427 | 0.560 | 0.046 | 2.045 |
| Union Twp | 0.473 | 0.378 | 0.435 | 0.487 | 0.058 | 1.831 |
| Frenchtown Boro | 0.432 | 0.243 | 0.334 | 0.485 | 0.290 | 1.784 |
| Readington Twp | 0.396 | 0.503 | 0.290 | 0.543 | 0.040 | 1.772 |
| Clinton Twp | 0.527 | 0.361 | 0.384 | 0.373 | 0.084 | 1.729 |
| Raritan Twp | 0.432 | 0.379 | 0.304 | 0.329 | 0.040 | 1.484 |
| Milford Boro | 0.453 | 0.181 | 0.481 | 0.324 | 0.000 | 1.439 |
| Hampton Boro | 0.517 | 0.218 | 0.204 | 0.254 | 0.118 | 1.311 |
| Stockton Boro | 0.481 | 0.120 | 0.334 | 0.322 | 0.000 | 1.257 |
| Califon Boro | 0.444 | 0.242 | 0.174 | 0.266 | 0.052 | 1.178 |
| High Bridge Boro | 0.415 | 0.137 | 0.362 | 0.202 | 0.055 | 1.171 |
| Bloomsbury Boro | 0.353 | 0.154 | 0.044 | 0.446 | 0.000 | 0.997 |
| Clinton Town | 0.307 | 0.180 | 0.232 | 0.008 | 0.000 | 0.727 |
| Lambertville City | 0.278 | 0.198 | 0.232 | 0.023 | 0.000 | 0.731 |
| GlenGardner Boro | 0.141 | 0.093 | 0.136 | 0.269 | 0.004 | 0.643 |
| Lebanon Boro | 0.264 | 0.036 | 0.026 | 0.279 | 0.000 | 0.605 |
| Flemington Boro | 0.352 | 0.069 | 0.040 | 0.010 | 0.000 | 0.471 |

same region. In this manner, the sprawl indicator measures hold potential for assessing the implications of policy and infrastructure factors such as zoning, sewers, highway accessibility, state and county planning policy, major versus minor subdivision processes, and others (Hasse, 2002).

One drawback of our sprawl indicators is their data intensive nature. The need for parcel-level data and detailed land-use/land-cover data at multiple time frames may limit the application of our sprawl measurement methodology in some locations. Even in the densely populated state of New Jersey, which has a good framework of basic geographic data layers, digital parcel data are currently available in only two of 21 counties. However, the situation is changing here in New Jersey and elsewhere. Digital parcel and land-use data are becoming more widely available through existing local and state government entities. The increasing availability of digital orthophotography, high-resolution satellite imagery, and on-screen digitizing tools make the development of municipal-scale land-use data much more practicable.

## Conclusions

The complex nature of urban sprawl requires sprawl indicator measures to employ multiple metrics. In this paper we developed metrics for five of the most significant spatial characteristics associated with urban sprawl for residential development. However, there are many other possible measures or variations to the measures employed here that hold potential for spatial analysis of urbanization in general and urban sprawl versus smart growth in the specific (Hasse, 2002). Our contention is that a housing-unit approach brings a new dimension in rescaling and temporal analysis of urban patterns complementing and improving on previous research that has explored the phenomenon of sprawl at coarser scales (Torrens and Alberti, 2000; Galster *et al.*, 2001; Ewing *et al.*, 2002).

As policy makers and stakeholders strive to steer development patterns away from sprawl and toward smart growth, an objective means of characterizing urban growth has become necessary. Sprawl indicator measures calculated at the housing-unit level provide an advantageous set of tools for evaluating and informing the development process. Sprawl is inherently a dynamic phenomenon, and our approach captures this dynamism by incorporating the land-use change time element. As urban patterns for a given region change with time, that changing dynamic reflected in changing sprawl indicator values may itself provide insight into the long-term patterns, underlying processes, and likely consequences of sprawling development compared to its smart growth alternative.

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