Measuring Urban Sprawl; How Can We Deal With It?

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Abstract

Measuring urban sprawl is a controversial topic among scholars who investigate the urban landscape. This study attempts to measure sprawl from a landscape perspective. The measures and indices used derive from various research disciplines, such as urban research, ecological research, and fractal geometry. The examination was based on an urban land-use survey performed in 78 urban settlements in Israel over the course of 15 years. Measures of sprawl were calculated at each settlement and then weighted into one integrated sprawl index through factor analysis, thus enabling a description of sprawl rates and their dynamics during a time period of two decades. The results reveal that urban sprawl is a multidimensional phenomenon that is better quantified by various measures.

Keywords: Urban Sprawl, Sprawl Indices, Land Use, Growth Management Policy

1. Introduction

During the past two decades urban sprawl has become a subject of particular interest among planners and policy-makers. Critics of sprawl all over the world are concerned by its many alleged negative impacts, such as lack of scale economies, which reduces the level of public services in the suburbs and weakens the economic base of central cities; increased energy consumption through encouraging the use of private vehicles, thereby causing traffic congestion and air pollution; and irreversible damage to ecosystems, caused by scattered and fragmented urban development in open lands (Ewing 1997; Burchell et al., 1998; Downs, 1998; Brueckner, 2000; Johnson, 2001). Since the 1987 World Commission on the Environment and Development and the 1992 Rio de Janeiro Congress on Sustainable Development, such terms as Growth Management, Smart Growth, Sustainability, New Urbanism, and Compact City have become familiar in the planning agenda. The concepts behind these terms being suggested as practical strategies to deal with negative impacts of urban sprawl (De grove, 1989; DLCD, 1992; Fulton, 1996; Jenks et al., 1996; Weitz & Moore, 1998; Nelson, 1999; Schiffman, 1999a; Johnson, 2001).

Not all planners, however, agree that sprawl has to be “dealt with” or restrained. Some consider it to be inevitable, harmless, or even positive (Mills & Hamilton, 1989, Gordon & Richardson, 1997, Brueckner, 2000). Common agreement exist as to its vast impact on urban landscape in Western countries (Hartshorn & Muller, 1992), as does a consensus on its ambiguity and lack of accurate definition and measures (Galster et al., 2001; Ewing et al., 2002). Ewing (1997) argued that there is no acceptable definition of the term urban sprawl. Others, like Burchell et al. (1998) have reported that not one study since the 1970s has succeeded in producing a clear, accurate, and full definition of this phenomenon. Hadly (2000) argued that one of the major problems concerning an analysis of sprawl stemmed from its poor, inadequate definition. In other words, we know sprawl is significant, but we are not yet sure what it is exactly or how to measure it. These questions are, of course, crucial to future studies that will attempt to analyze the impact of sprawl on the urban landscape (Torrens & Alberti, 2000).

Our purpose in this study is to address the question of how urban sprawl can be measured. Based on the literature, it is clear that urban sprawl is a complex phenomenon that, besides not being defined unequivocally, is difficult to quantify and measure accurately. Hence, moving from “sprawl” to “compact” form is more likely to be a direction on a continuum rather than a fixed and measurable category. However, several studies in recent years have tried to deal with this question by suggesting a variety of urban sprawl measures (Torrens & Alberti, 2000; Galster et al., 2001; Malpezzi & Wen-Kai, 2001). Although some of these measures were tested in empirical studies, many of them still remain theoretical or tested only in the context of the ecological research discipline, but not applied in urban research. This study implements various measures of sprawl that are suggested in the literature, investigating the most efficient way to use them to measure the phenomenon. It identifies the relationships among and the changes in their values during the period investigated, as well as describes both the static and the dynamic development pattern of sprawl in a large sample of urban settlements.

Notwithstanding the copious discussion on sprawl in the literature, the absence of empirical evidence in support of the various positions is still clear. Therefore, empirical studies, like the current one, are important in light of the ideological and practical argument that exists between those who oppose and those who side with this phenomenon. Empirical studies contribute to our understanding of the essence of sprawl, bringing quantitative knowledge into the discussion and suggesting possible solutions (Batty et al., 1999). Without this knowledge, ideological and practical discussion on urban sprawl and the effectiveness of a growth-management policy remains only in the conceptual and speculative realm (Torrens & Alberti, 2000). The next section will present various measures of sprawl gathered from a literature review. Section 3 defines the framework of this study; the data and the region investigated are described in Section 4. The main empirical results are contained in Section 5. Finally Section 6 presents the conclusions.

2. Measures of Sprawl

Urban sprawl is a form of spatial development, characterized by low densities, scattered and discontinuous "leapfrog" expansion, and segregation of land uses, encouraging the massive use of private vehicles and strip-malls; this form of development is found mainly in open, rural lands on the edge of metropolitan areas (Peiser, 1989; Ewing, 1997; Burchell et al., 1998; Hadly, 2000; Razin & Rosentraub, 2000). The phenomenon of urban sprawl, often referred to as suburbanization, started at the end of the industrial era, and it has continued since throughout the world, but especially in Western countries (Belser, 1960; Harvey & Clark, 1965; Gans 1967; RERC, 1974; Jackson, 1985; Mills & Hamilton, 1989). More recent patterns of sprawl are the American "edge city" (Gareau, 1991) and the European Functional Urban Region (FUR); these represent the phase of disurbanization in the cyclic model of the development process of metropolitan regions (Klaassen et al., 1981; Van Der Berg et al., 1982). In fact, sprawl has been conceptualized in recent studies as a multidimensional phenomenon that requires a different set of measures for each dimension (Torrens & Alberti, 2000; Galster et al., 2001; Ewing et al., 2002). Most sprawl measures suggested in the literature can be divided into five major groups: growth rates, density, spatial-geometry, accessibility, and aesthetic measures.

Growth Rates - In terms of growth rates, urban sprawl is defined as a condition in which population growth rates in the suburbs are higher than inside the central city (Jackson, 1985). Another popular growth-rate measure is the "Sprawl Index" (SI) or "Sprawl Quotient," defined as the ratio between the growth rate of built-up areas and the population growth rate in a certain area. A quotient higher than 1 implies urban sprawl (Weitz, 2000; Hadly, 2000).

Density - This is the most popular sprawl measure (Galster et al., 2001) and, some will argue, the one that best represents the phenomenon (Maret, 2002). There are various types of densities, as well as many ways and scales to measure it (Churchman, 1999; Burton, 2000; Chin, 2002). Density is defined as the ratio between the amount of a certain urban activity and the area on which it exists. Urban activity can be defined as the amount of residential units, number of residents, or employees (Razin & Rosenrtaub, 2000).

In terms of density, sprawl is defined as a condition in which density is relatively low or decreases during a certain time period. Another popular density measure that quantifies the latter definition is the density gradient, which is the constant in the negative exponential model (Batty & Longley, 1994; Alperovich, 1995). During the past few decades, density gradients have been falling constantly in developed as well as developing countries (Ingram, 1998), which well proves the universality of urban sprawl.

Spatial-Geometry - This constitutes the largest group of measures. There are numerous geometric measures, most of which have been adopted from ecological research (Turner, 1989; McGarigal & Marks, 1995) or from fractal geometry (Batty & Kim, 1992; Batty & Longley, 1994; Torrens & Alberti, 2000; Herold & Menz, 2001). Geometric or ecological measures quantify two main characteristics of the urban landscape: configuration and composition. Configuration refers to the geometry of the urban built-up area, and composition to its level of heterogeneity. An urban area will be considered sprawling as long as its geometric configuration is irregular, scattered, and fragmented, and its land-use composition more homogenous and segregated.

Some common measures in this category are leapfrog or continuity (Galster et al., 2001), measure of circularity (Gibbs, 1961), fractal dimension and Mean Patch Size (MPS) (Batty & Kim, 1992; Batty & Longley, 1994; Benguigui, 1995; Torrens & Alberti, 2000; Herold & Menz, 2001) - all of these quantify the level of scatter and fragmentation of the urban landscape. The percentage of different land-uses quantifies its level of heterogeneity (McGarigal & Marks, 1995; Frenkel, 2004b).

***Accessibility* -** Sprawl is defined as a condition of poor accessibility, followed by the massive use of private vehicles (Ewing 1994, 1997; Ewing et al., 2002), or as Al Gore very simply put it, "A gallon of gas can be used up just driving to get a gallon of milk.[1]" Accessibility can be quantified by measuring road length, road areas, and the traveling times of households (Hadly, 2000). Another way to measure accessibility is to calculate the fractal dimensions of road networks (Benguigui, 1995). Some ecological measures are useful to measure accessibility, such as "Mean Proximity Index" (MPI) (Gustafson, 1998; Torrens & Alberti, 2000). Another group of accessibility measures is used in transportation models, such as the gravity or logit models (Torres & Alberti, 2000).

***Aesthetic measures* -** Sprawl is often considered a boring, homogenous form of development (Gordon & Richardson, 1997; Fulton, 1996). Being subjective by definition, it is difficult to measure and quantify the aesthetics of sprawl. However, several recent studies have attempted to define archetypes of urban development or sprawl, such as residential sprawl or strip-malls sprawl, and to compare various landscapes to those archetypes. It seems that much work is still needed in this area (Torrens & Alberti, 2000).

3. Methodology

3.1 Research Framework

This study is a first attempt to measure urban sprawl in Israel and its dynamics during the past two decades from a landscape perspective. Urban sprawl in Israel started two decades ago, but has not yet been empirically measured or characterized. Major processes that influenced sprawl in Israel were the rise in the standard of living and in residential floor area per person, consumer preference for low-density, single-family housing in the suburbs, and the arrival of one million immigrants from the former USSR during the 1990s -- all of which led to a massive transformation of agricultural land into urban land-uses all over the country and perhaps to sprawl-like patterns of development (Gonen, 1995; Gonen, 1996; Schiffman, 1999b). Scholars and planners in Israel are concerned with sprawl's negative impacts and its leading to wasteful land consumption, especially given Israel's unique condition as a small country with limited land resource, but at the same time with relatively high population growth rate, in contrast to other Western countries (Frenkel, 2004a). Hence, measuring sprawl in Israel is crucial to a better management of its land resource.

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[1] Quote from a speech by Al Gore during his campaign for the U.S. presidency, January 1999 (http://www.greenclips.com/00issues/139.htm).

Two major issues were investigated within the framework of this study. The first is the question, how can we measure urban sprawl? Is urban sprawl a measurable phenomenon? The second question is, does urban development in Israel comply with the definition of sprawl as we know it?

Based on a review of the literature, we hypothesize that sprawl is a complex phenomenon that cannot be measure by only one or two measures, as is often done in many urban studies. Hence, we assume that its various dimensions are independent and not significantly correlated with one another. In order to examine this hypothesis an urban land-use survey was performed in 78 Jewish urban settlements and then compared with a survey performed by the Israeli Central Bureau of Statistics (CBS) 15 years earlier. Measures of sprawl were defined, calculated, and compared, enabling the description of sprawl rates and its dynamics during the time period investigated. The results of this study provide a rather comprehensive and useful database on urban sprawl in Israel, as well as a better understanding of what sprawl is and how it can be measured from a landscape perspective.

3.2 The Sample

A sample of 78 settlements was included in the land-use field survey, representing 67% of all Jewish urban settlements in Israel.[2] The sample covers about 4.76 million residents, or 78% of all residents in urban settlements in the country and 71% of the entire Israeli population (CBS, 2004). The urban built-up areas that were mapped in this survey add up to 624.5 square km, constituting 55% of all built-up areas in Israel (Frenkel, 2004a). The sample includes settlements from all six districts and all four metropolitan regions of Israel, as well as settlements of different metropolitan functionality. It includes all four metropolitan core cities in Israel (Jerusalem, Tel-Aviv, Haifa, and Beer Sheva), 96% of the inner and middle-ring towns, and 72% of the edge cities and towns in peripheral regions. Settlement sizes vary from small towns of 2,000-5,000 residents to medium-size towns of up to 100,000 residents and large towns with more than 100,000 residents. The sample contains almost all Jewish urban settlements above 20,000 residents, half of the urban settlements with 10,000-20,000 residents, and one fourth of the urban settlements with fewer than 10,000 residents. The sample, therefore, well represents all Jewish urban settlements from all perspectives: spatial location, metropolitan functionality, and size.

Two land-use surveys were conducted for each urban settlement: a basic survey performed by the Israeli CBS in the mid 1980s (CBS, 1997) and a second survey, methodologically consistent with the first one, performed by the authors at the end of 2002. Both land-use surveys provided the relevant parameters enabling the comparison of two sets of sprawl measures, one for the beginning (t_0) and the second for the end (t_1) of the period investigated.

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[2] Arab settlements were not included in the sample because of their unregulated development of land uses. The development of their physical pattern did not result from controlled planning, but was constrained by historical causes connected to the lack of statutory planning, land-ownership patterns, and social norms concerning land development accepted by Arab society and expressed in a multi-generation building pattern, which justifies a separate investigation. We were also not able to include rural settlements because of the lack of information regarding their land-use composition during the time period investigated. However, we did include small urban settlements, which are semi-rural by character.

3.3 Unit of Investigation

Researchers tend to measure urban sprawl on either a metropolitan scale as mostly used in the U.S. (Razin & Rosentraub, 2000; Ewing et al., 2002, Wolman et al., 2004) or on smaller scales of towns or neighborhoods, mostly used in Europe (Batty & Longley, 1994; Burton, 1996, 2000; Hasse & Lathrop, 2003). Our study investigated sprawl on a town scale. The selection of this investigation unit enabled us to obtain a large database, sufficient for examining statistical differences in the sprawl variables between the selected urban settlements[3]. Likewise we could test the existence of this phenomenon in a large variety of types of urban settlements. Furthermore, the available basic survey from the mid 1980s preformed by the Israeli CBS and accessible to our examination, was used in our study as a starting point to test the dynamic of the sprawl phenomenon in time and space dimensions.

Hence, the unit of investigation was defined as the urban built-up area inside the municipal border of an urban settlement (Figure 1). The boundaries of the built-up areas of each of the urban settlements selected were marked on city maps scaled 1:10,000-1:12,000 and verified through aerial photography and field surveys. Open non-used land was excluded from the total area within a city's jurisdiction. The final built-up areas, therefore, included only the areas that were in use for various purposes within the locality's jurisdiction.

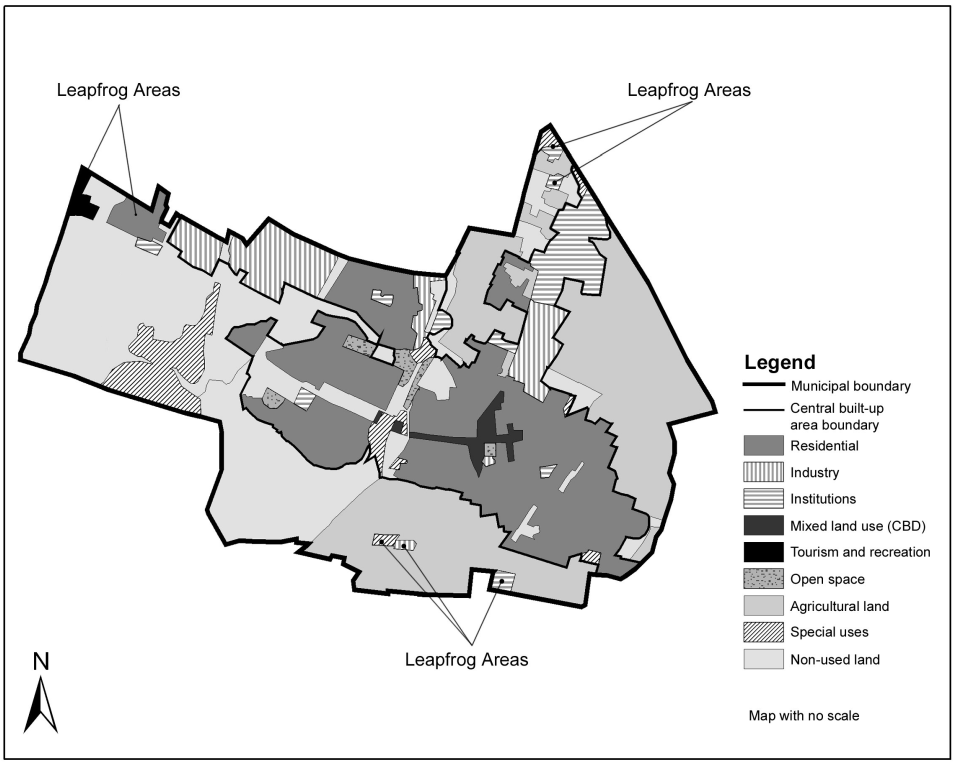

Figure 1: Scale Unit - The Urban Built-up Area (Central Area + Leapfrog Areas), Example of the City of Rishon Letzion (200,000 residents)

[3] Unlike the U.S.A. where dozens of metropolitan regions and hundreds of urbanized areas exist within the metropolitan regions, Israel has only four metropolitan regions.

We divided each built-up area into two major groups: the central built-up area and the leapfrog areas (see Figure 1). The central built-up area contains most of the residential land and other built-up land-uses, as well as inner public open spaces or natural open spaces, agricultural lands, and inner non-used lands surrounded by built-up areas. Leapfrog areas are built-up land-uses that are located separately at a distance from the central built-up area, but have a functional linkage with it (residential, industrial, or institutional). We excluded from this category special leapfrog areas that were identified through the field survey, such as built-up land uses that do not have any direct functional linkage with the urban settlement (regional installations, interchanges, interurban highways, or army camps).

3.4 Urban Sprawl Variables

Torrens & Alberti (2000) suggested an analogy between urban built-up areas and open spaces, or natural lands, as a practical method for quantifying sprawl, using measures “adopted” from the ecological discipline. We adopted this perspective, and therefore referred to polygons of different urban land-uses as “patches” and characterized the urban area in terms of “configuration” and “composition” (see Table 1). We then defined three dimensions of sprawl derived from those two characteristics: density, scatter (or fragmentation), and mix of land-uses. Next, five groups of sprawl variables were derived from each of those dimensions: population density, irregularity of the shape of the central built-up area boundary, fragmentation, land-use segregation, and land-use composition. Each group contained 1-6 specific measures as presented in Table 1; all in all, we computed 13 measures of sprawl.

Table 1: Characteristics, Dimensions, and Indices of the Built-up Area

<table>
<tr><th>Characteristics</th><th>Dimensions</th><th>Variables</th><th>Indices</th></tr>
<tr><td rowspan="7">Configuration</td><td rowspan="2">Density</td><td rowspan="2">Population density</td><td>Gross population density</td></tr>
<tr><td>Net population density</td></tr>
<tr><td rowspan="5">Scatter</td><td rowspan="2">Irregularity of the shape of the central built-up area boundary</td><td>Fractal dimension</td></tr>
<tr><td>Shape index</td></tr>
<tr><td rowspan="3">Fragmentation</td><td>Gross leapfrog index</td></tr>
<tr><td>Net leapfrog index</td></tr>
<tr><td rowspan="2">Mean patch size</td></tr>
<tr><td rowspan="7">Composition</td><td rowspan="7">Mixed land use</td><td>Land-use segregation[1]</td></tr>
<tr><td rowspan="6">Land-use composition</td><td>Residential area</td></tr>
<tr><td>Industrial area</td></tr>
<tr><td>Public institutions land-use area</td></tr>
<tr><td>Mixed land use</td></tr>
<tr><td>Tourism and recreation area</td></tr>
<tr><td>Special land uses[2]</td></tr>
</table>

1. Not measured in this study.

2. Sport centers, cemetery, urban interchanges, bus and railway stations.

As some researchers have suggested, moving from “sprawl” to “non-sprawl” form is more likely to be a direction on a continuum rather than a fixed, measurable category (Pendall, 1999; Johnson, 2001). Based on this assumption, we defined directions on a continuum for each sprawl measure implemented in our study. For example: relatively low density means sprawl while high density means non-sprawl or compact development; a high percentage of residential land use in an urban area means it is homogenous and non-mixed, thus sprawling, while a lower percentage of residential land use implies a mix of land-uses and heterogeneity, thus compact. A complete explanation of all sprawl measures used in our study and the direction of their impact on sprawl is presented in Annex A.

3.5 The Integrated Sprawl Index

In order to compare levels of sprawl among settlements, a method of weighting all 13 measures to produce a single integrated sprawl index is suggested. Several methods of weighting measures of sprawl have recently been discussed, such as Z-score scaling, factor analysis, and cluster analysis (Galster et al., 2001; Ewing et al., 2002; Wolman, 2004). Still, most of the sprawl studies generally focus on one or two types of measures, usually taken from the same research discipline. Studies in which population sizes and densities are implemented generally have no reference to geometric or ecological measures (Galster et al., 2001; Ewing et al., 2002; Shoshany & Goldshleger, 2002), and vice versa (Herold & Menz, 2001). Studies that combine density and scatter dimensions of sprawl usually lack the third dimension, land-use composition (Benguigui et al., 1998). Our study suggests a weighted combination of the three dimensions or sets of completely different measures of sprawl, adopted from different disciplines: population-density measures, geometry and ecological indices, and land-use composition.

Factor analysis was chosen as a method of weighting all 13 measures to produce one integrated sprawl index. We found it suitable as a data reduction method when some of the variables are linearly correlated to one another (Kim & Muller, 1978). Factor analysis was first performed for all sprawl measures in t_1 (year 2002), divided into two major groups of measures, or two dimensions of sprawl: density and scatter (related to the configuration dimension), and mix of land uses (related to the composition dimension). Each group contained 6-7 measures of sprawl. The analysis of each group produced three main factors[4], with a total explained variance of 70%-80%. Each factor is a linear combination of all measures in the group, with one or two dominant measures[5] that define its unique "identity." Each factor received a positive or negative sign according to its relative contribution to sprawl, based on the previously defined continuum (see Annex A). The signs were given to the entire linear combination of measures in each factor, not only to its dominant measures.

In the next step, we computed a weighted sprawl score for each of the two dimensions (density & scatter[6], and mix of land uses), according to the percentage of the explained variance obtained by the variables included in each of the two dimensions. We then computed a final weighted sprawl index as a weighted average of the two sprawl scores, based on the explained variance of each one. For convenience, the weighted sprawl index was normalized to a positive Z score, with the most compact settlement receiving a score of zero and the most sprawling settlement a score of 524.7. We call this scale the Integrated Sprawl Index for t_1. In order to describe the dynamics of sprawl during the period investigated, we also computed an integrated sprawl index for t_0. For the sake of consistency, which allowed us to compare the

[4] Main factors were defined by eigenvalues>1.

[5] Dominant measures were defined as those with an absolute value of the component coefficient greater than 0.5. For example, a factor whose absolute values of gross and net density coefficients were greater than 0.5 and whose absolute values of all other measure coefficients were smaller than 0.5 was identified as the "density factor."

[6] Density and scatter were united into one sprawl dimension for convenience.

two integrated indices (t_1 and t_0), we transformed all sprawl measures in t_0 to Z scores comparable to t_1 (a similar methodology was implemented in a study by Ewing et al., 2002)[7].

4. The Challenge of Using Sprawl Measures

Average results of each group of sprawl configuration measures show that most urban settlements in Israel during the last two decades have become denser, their geometrical shapes more regular and compact, leapfrog areas smaller, and mean patch sizes of built-up areas larger. However, land-use composition did not dramatically change during the time period investigated (Table 2).

Table 2: Sprawl Measures (Average Values*) for 78 Urban Settlements in t_0 and t_1

Dimension	Sprawl measure	Mid 1980s (t_0)	2002 (t_1)	% change (t_0-t_1)
Configuration (Density & Scatter)	Gross population density (pop/sqkm)	6,676 (3,432)	7,609 (3,710)	13.9
	Net population density (pop/sqkm)	11,201 (5,349)	12,243 (5,525)	9.9
	Fractal dimension	1.287 (0.038)	1.273 (0.036)	-1.1
	Shape index	2.581 (0.867)	2.424 (0.817)	-6.1
	Gross leapfrog index (%)	6.5 (10.5)	5.2 (9.3)	-20.0
	Net leapfrog index (%)	3.5 (8.5)	2.8 (8.3)	-20.0
	Mean patch size (hectares)	44.1 (26.3)	52.9 (23.0)	20.1
Composition (mixed land use)	Residential area (%)	66.7 (16.9)	67.9 (14.7)	1.8
	Industrial area (%)	11.9 (11.6)	12.4 (9.6)	4.2
	Public institutions land-use area (%)	4.9 (5.1)	4.7 (4.5)	-4.1
	Mixed land use and malls (%)	3.3 (3.3)	4.6 (3.0)	39.4
	Tourism and recreation area (%)	1.6 (4.6)	1.5 (4.3)	-6.3
	Special land uses (%)	4.0 (6.3)	4.2 (4.7)	5.0

* Standard deviation is given in parentheses.

[7] We did this by subtracting the averages of sprawl measures in t_1 from measures in t_0 and dividing them by standard deviations of sprawl measures in t_1. We then multiplied each vector of Z scores (meaning a row of 13 normalized sprawl measures for each settlement in t_0) by the component score-coefficient matrices obtained in the factor-analysis procedure for t_1, thus resulting in two sprawl scores for each dimension in t_0. The scores were weighted by the percentage explained variance and normalized to a positive Z score, which represents an Integrated Sprawl Index for t_0 that consistent and comparable with the one for t_1.

4.1 Density Measures

As density is the most popular sprawl measure, we will elaborate on the density results obtained in our study. The average gross and net population density has risen by 13.9% and 9.9%, respectively, in Israeli urban settlements during the period investigated. In terms of density, sprawl is defined as a state in which density is either relatively low and/or becoming lower during a certain time period. Based on these two categories, we divided Israeli urban settlements into four major groups (see Figure 2). The border lines that distinguish each of the four groups indicate the average gross-density measure of the whole sample in 2002 (x axis) and the zero growth rate of the gross density during the period investigated (y axis).

It is clear from Figure 2 that the growth rate in population density between t_0 and t_1 in most of the settlements is above zero. However, the gross density in most of these settlements at the end of the time period investigated is below the average of the whole sample. This means that most of the settlements where density increased are still sprawling in relative terms.

One group of settlements is definitely sprawling (Group 4), for its density is relatively low and becoming even lower over time. Most settlements in this group are semi-rural or peripheral settlements. In contrast, another group is definitely compact (Group 1), for its density is relatively high and becoming higher over time. Most settlements in this group are relatively large cities, where denser development is usually expected because of higher land rents.

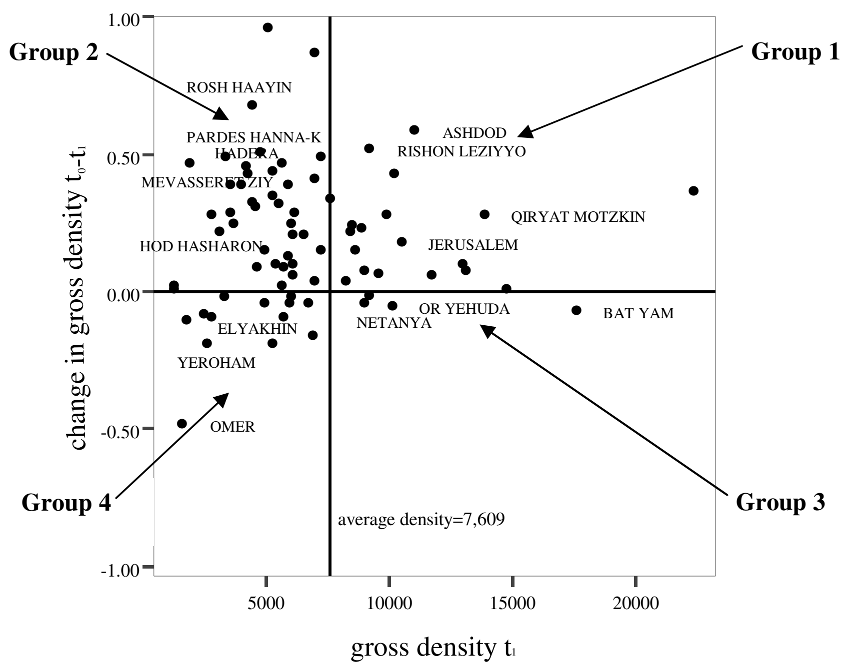

Figure 2: Gross Urban Density in t_1 Versus Change in Gross Urban Density between t_0 and t_1

Groups 2 and 3 are variations of sprawl or compactness. Group 2, the biggest group in our sample, contains about half of the urban settlements. Although density has risen in this group, we consider the group rather sprawling: some of the settlements in this group are semi-rural, suburban, or peripheral settlements with average densities lower than 5,000 residents per sqkm. During the 1990s, much rural land within those settlements was given over to residential use. Former agricultural farms were divided into smaller parcels, enabling a massive development of detached residential units, purchased by middle and upper-class households. Thus, although average densities in this group of settlements have risen, their development pattern of suburban detached-houses is characteristically sprawling. Another part of this group consists of settlements with average densities higher than 5,000 residents per sqkm. These are bigger and older cities, where many new immigrants were absorbed during the 1990s in either vacant apartments in older neighborhoods or in new, densely built neighborhoods.

Group 3, which contains only four urban settlements, is the smallest group in our sample. Average densities in this group are relatively high, but becoming lower over time. Negative density gradients in this group can be explained by either lower rates of population growth owing to population aging, or high growth rates of non-residential areas. Either way, density decline in this group can be considered sprawl.

To conclude, although the growth rate of built-up areas during the period investigated was high (26%) and almost all additional built-up areas came at the expense of open and rural lands, population growth rate was higher (44%)[8]; thus, the average gross density of the sample increased by 13.9%. This positive density growth rate may have resulted from the high capacity of both cities and smaller towns, where part of the new population could have been absorbed in an in-fill manner inside the existing urban built-up areas. This high capacity could have resulted from a high amount of vacant dwellings in older cities, where new immigrants were usually absorbed, or alternatively, from the high amount of available land inside smaller quasi-rural settlements, where agricultural land was transformed into urban land and filled in by high amounts of lower-density, detached single-family residential units. Thus, average densities in those settlements increased although the development pattern in this case was rather sprawling because of the high percentage of detached residential units. Our conclusion, therefore, is that density cannot be a sole parameter of sprawl and that further indices are needed in order to quantify this phenomenon.

4.2 Scatter Measures

Shape index and Fractal measures show the level of irregularity of the central built-up area perimeter of the settlement. Shape and fractal index values have slightly decreased on average over time. Thus the level of irregularity of the urban form in most of the settlements did not change much and there was a slight tendency toward filling the form in a compact manner. Still in 29 urban settlements, we found that shape index and fractal values have increased, pointing to a sprawl configuration. In addition, shape and fractal measures were found to be higher and to increase over time (thus more sprawling) in mountainous topography, as has similarly been found in other studies (O'Neill et al., 1988).

As for leapfrog measures, we found that most settlements (70%-80%) did not have leapfrog residential areas at all. About 50% of the settlements had non-residential leapfrog areas that were reasonably located outside the central built-up area, such as for industrial areas. We also found that, on average, leapfrog index values decreased during the period investigated (by 20%), proving the assumption that leapfrog development tended to be filled as time passed; hence, sprawl may be considered a temporary condition (Peiser, 1989; Brueckner, 2001). Although most of the settlements in our sample are not developed in a scattered leapfrog

[8] The settlement sample size adds up to 3.3 million residents on 493.8 sqkm in t_0, and to 4.8 million residents on 624.9 sqkm in t_1.

manner, leapfrog areas were found to be significant in 16 settlements, with sums up to 11% of the entire urban built-up area, and to be increasing over time.

Mean Patch Size (MPS) of built-up areas increased about 20% during the time period investigated. Like the result with the leapfrog measures, this proves that most urban settlements in Israel are developed in a non-scattered way. However, the MPS measure decreased in 12 of the 78 settlements, thus development in those settlements was more scattered and sprawling. The results imply that urban development tends to be more scattered and fragmented in old, semi-rural settlements, where rural parcels were divided and transformed into residential parcels over the course of decades. An opposite pattern seems to characterize pre-planned new settlements, where most of the residential areas were developed simultaneously. Further investigation is needed in order to confirm this assumption.

4.3 Land-use Composition

The proportion of residential areas did not dramatically change over time. About 67% of the urban built-up areas of the settlements are residential areas, 12% are industrial areas, and each of the other land-use categories constitutes about 1%-6% of the urban built-up area. Most of the new built-up areas were developed on open, rural lands outside the central built-up areas. During the period investigated, the inner, non-used areas in the built-up areas of the 78 urban settlements constricted by only 2.2%. This finding confirms the assumption that it is easier to build on vacant lands than to develop in an in-fill manner inside existing neighborhoods (Ewing, 1994). We also noticed a rise in industrial areas on the fringes of settlements, as opposed to a decline in commercial areas inside them. We explain this finding by the rise of commercial malls near industrial areas in Israel since the 1990s, as well as the parallel decline in commercial activity inside old neighborhoods.

We also found that residential areas in all the settlements exceeded 50% of the total built-up area and that there was little variance among settlements in regard to this parameter. This finding proves the essential difference between open lands and urban lands. Open, natural lands, where ecological measures of land-use composition are implemented, are much more heterogeneous and diversified than urban built-up areas. Although variation in land-use composition exists between different groups of settlements (Frenkel, 2004b), the fact that urban landscapes are less diversified than natural landscapes necessitates the use of other composition measures in future studies.

Based on these results, especially those referring to the settlements' configuration dimension, we may conclude that most urban settlements in Israel have become less sprawling and more compact during the past two decades. This relatively compact pattern of development uniquely characterizes Israel, in contrast to North American countries. It may result from limited land resources causing a more regulative planning policy and denser, more compact forms of urban development. But does it mean, that urban sprawl does not exist at all in Israel? We will discuss this question in the next section.

5. Level of Sprawl in Israeli Urban Settlements

5.1 Sprawl Index

The level of sprawl was obtained from computing the integrated sprawl index for each of the urban settlements in the sample through factor analysis. Factor analysis was employed for the two dimensions of sprawl examined in this study: configuration and composition. The results are presented in Table 3.

Table 3: Factor Analysis Results in t_1, Major Sprawl Indices, and Factor Loading

Urban Built-up Area Characteristic	Sprawl Dimension	Major Factor[1]	Dominant Measures in Each Factor[2]	Component Score	Direction of Impact on Sprawl (+ or -)[3]	Percentage Variance	Cumulative Percentage of Variance
Configuration	Density & Scatter	Irregularity of the central built-up area perimeter	F	0.962	+	34.9	83.3
			SH	0.918			
			Mps	-0.469			
		Population density	D_g	0.961	-	25.1	
			D_n	0.971			
		Leapfrog	LFI_g	0.923	+	23.3	
			LFI_n	0.933			
Composition	Mixed Land Use	Residential and industry, weighted index	LU_1	-0.838	-	33.7	72.3
			LU_2	0.925			
		Commerce and institutions land use, weighted index	LU_3	0.842	-	20.3	
			LU_4	0.651			
		Leisure land use (tourism and special uses), weighted index	LU_5	0.869	-	18.4	
			LU_{6in}	0.560			

1. Major factors were defined by eigenvalues>1.

2. Detailed definition of each sprawl measure see Annex A.

3. Each factor received sign (positive or negative) according to its positive or negative contribution to the level of sprawl. This determination was made in the computation of the integrated sprawl index (see Section 3.5).

For each factor in Table 3 only the dominant measures is presented, when the absolute value of the Rotated Component Matrix Loadings was higher than 0.5. The configuration dimension has three factors: the irregularity factor, the density factor, and the leapfrog factor. Although the MPS loading coefficient is lower than 0.5, it is interesting to introduce this measure in regard to its interaction with shape/fractal measures. We realized that the more irregular the shape of the central built-up area (higher values of shape or fractal indices), the more fragmented it becomes (lower MPS values). To the best of our knowledge, correlations between shape indices and patch indices have so far been examined only in ecological research (McGarigal & Marks, 1995); and since their results vary, they can be interpreted in both ways. Hence, further investigation on this subject is needed in urban studies, as well.

The composition dimension also has three factors: the residence-industry factor, the commerce and services factor, and the leisure factor. A settlement with more residential area has less industrial area. Commercial and service areas are positively correlated with each other, as are areas of leisure (tourism and special uses). Factor analysis was found to be efficient in this case not only as a data reduction method, but also as method of identifying major interactions between different sprawl measures. Not all of these interactions could have been identified by simple linear correlations.

Based on a linear correlation between the computed integrated sprawl index and each of the sprawl measures, we found a relatively higher dominance of density, shape/fractal, residential, commercial, and industrial land-use measures when measuring urban sprawl. This is in contrast to leapfrog, MPS, and other land-uses, which are apparently less important when measuring sprawl on a municipal scale.

Additionally, residential land-use percentage is highly correlated with the land-use composition score (R_p=0.939, with a significance of 99%). This means that the residential land-use measure well represents in itself the urban land-use composition. What is lacking is a better measure of the landscape's level of fragmentation and segregation, ascertained by employing other geometric measures (lacking in this study), such as accessibility, proximity, and contagion index of land-use polygons or patches[9]. Further development of these sprawl measures is needed in future studies.

5.2 Ranking Urban Settlements According to the Level of Sprawl

Based on the integrated sprawl index value (Z_i) in t_0 and t_1, each of the settlements in the sample was ranked on a relative "sprawl scale." The most sprawling settlement received the highest Z_i value, and the most compact settlement the lowest. We then divided the sample into four "sprawl clusters" (see also Figure 3):

- Cluster 1: "highly compact," when $0<Z_i<200$
- Cluster 2: "compact," when $200<Z_i<300$
- Cluster 3: "sprawling," when $300<Z_i<350$
- Cluster 4: "highly sprawling," when $Z_i>350$

The sprawl scale in both t_0 and t_1 provides us with a relative measure of comparison among settlements, as well as an examination of each settlement's sprawl dynamics over a period of two decades. In general, the integrated sprawl-index levels range from 12.8-631.9, with an average sprawl level of 310.3 in t_0, to a range of 0-524.6 and an average sprawl level of 286.8 in t_1. This means that urban settlements became a little more compact during the 1980s and 1990s, a finding that is in contrast to the general belief that most settlements in Israel developed in a sprawl-like manner during those decades. We also found that most settlements (72%) did not change their sprawl cluster dramatically over time.

The highly compact settlements are usually large, denser cities, while highly sprawling settlements are usually small and semi-rural. Generally there is high and negative correlation between the level of sprawl and the size of a settlement, as has been found in similar studies (Ewing et al., 2002). Sprawling settlements usually have higher land consumption than do

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[9] We know only part of the level of fragmentation by the MPS measure, but only for all built-up areas and without further specification of each land use.

compact settlements. We found that 75% of the sample's population resided in more compact settlements (sprawl clusters 1-2), which encompassed only 67% of the total built-up area of the settlements in the sample. Thus, sprawling urban settlements are less efficient in using land than are compact urban settlements.

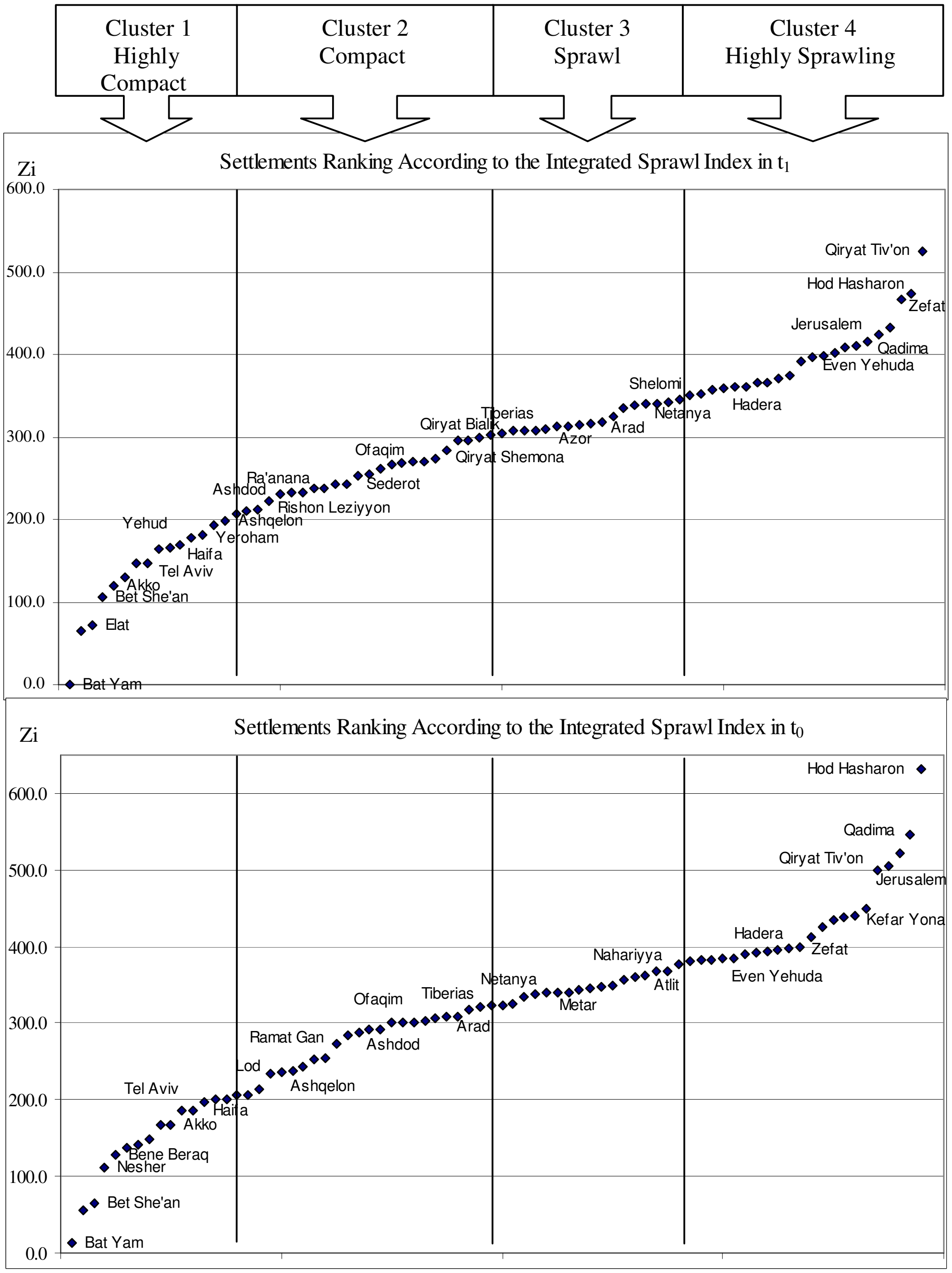


Figure 3: Rank of Urban Settlements in Descending Order, by Integrated Sprawl Index in t_0 and t_1

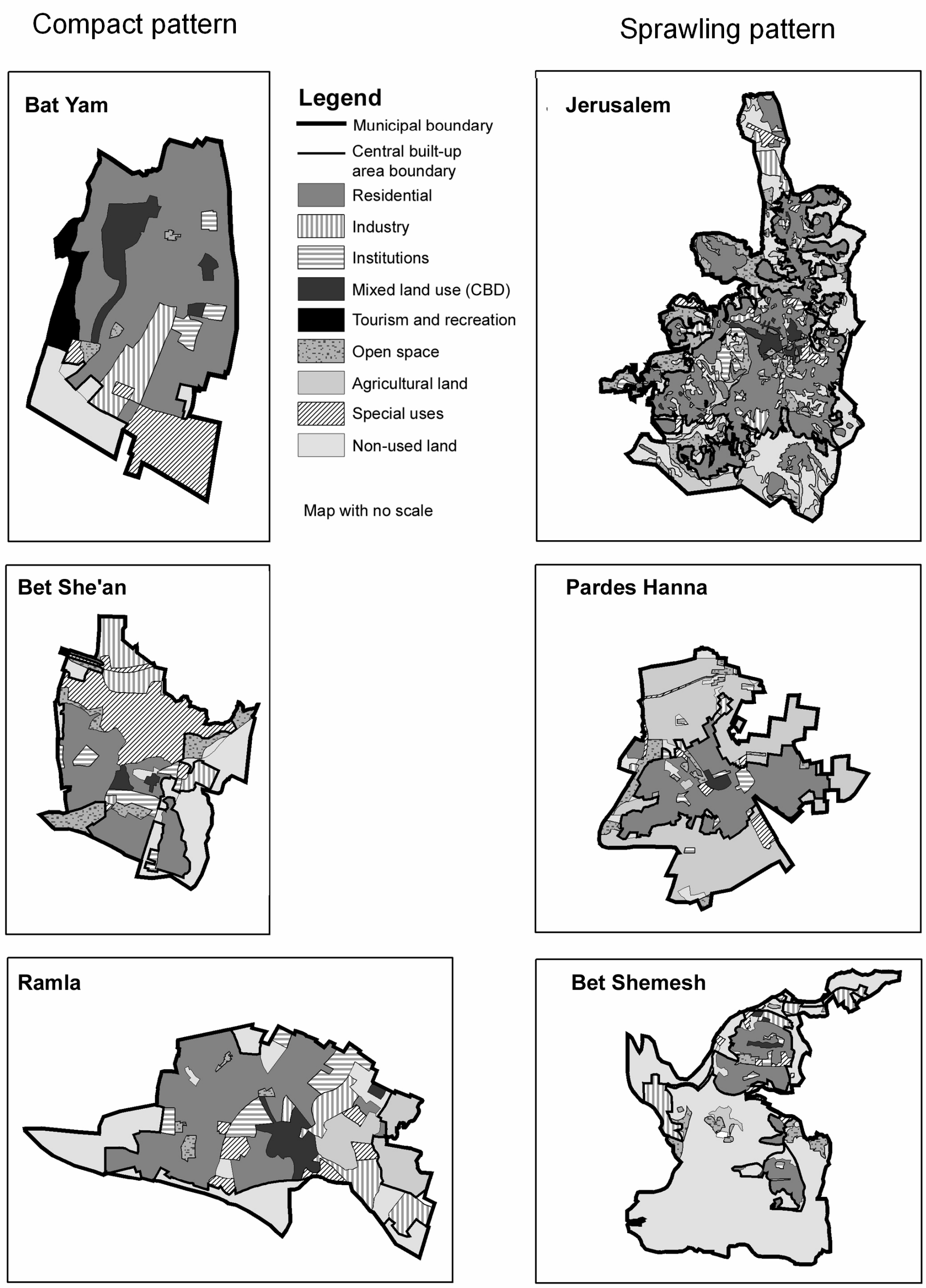
Another major finding is that the growth rates of both population and built-up areas in sprawling settlements (sprawl clusters 3-4) during the time period investigated were relatively high: 52.5% and 29.7% as opposed to 39.9% and 24.5%, respectively, in compact settlements (sprawl clusters 1-2) (see Table 4). This means that sprawling settlements have a higher capacity and are apparently more attractive to new residents than are compact settlements. It seems that there is higher consumer preference for residing in smaller, more sprawling settlements. Although their density increased dramatically during the past two decades, sprawling settlements are not expected to transform into compact, dense cities. We assume that sprawling settlements are more likely to reach the saturation phase as soon as all their vacant lands are filled with detached houses. Then, other, new sprawling settlements might be developed in order to meet these consumer preferences.

Table 4: Population and Urban Built-up Area Growth Rates During the Period Investigated, by Sprawl Cluster

	Sprawl Cluster in t_1				
Variable	Cluster 1 Highly Compact	Cluster 2 Compact	Cluster 3 Sprawl	Cluster 4 Highly Sprawling	Total
Number of Settlements	15	23	18	22	78
Population Size in t_1	1,461,100	1,598,300	562,300	1,130,497	4,752,197
Built-up Area in t_1 (sq/km)	189.3	186.4	87.4	161.9	625.0
Population Increase from t_1-t_0	299,422	573,154	177,162	405,642	1,455,380
Increase in built-up Area from t_1-t_0 (sq/km)	26.2	47.8	19.0	38.2	131.1
Population Growth Rate from t_1-t_0 (%)	25.8%	55.9%	46.0%	56.0%	44.1%
	39.9%		52.5%		
Built-up Area Growth Rate from t_1-t_0 (%)	16.1%	34.5%	27.7%	30.8%	26.6%
	24.5%		29.7%		
Population Density in t_0	7,124	7,395	5,629	5,858	6,676
	7,249		5,777		
Population Density in t_1	7,720	8,572	6,435	6,983	7,604
	8,143		6,791		
Density Growth Rate from t_1-t_0 (%)	8.4%	15.9%	14.3%	19.2%	13.9%
	12.3%		17.6%		

Inevitably, we did not find a high correlation between the level of sprawl and the average population density. For example, average density in sprawl cluster 3 is less than in sprawl cluster 4. Similarly, average density in sprawl cluster 2 is higher than in sprawl cluster 1 (Table 4). Hence, even though a density measure is prevalent in urban research in general and in sprawl research in particular, it still cannot substitute for the integrated sprawl index that encompasses other characteristics of the sprawl phenomenon, such as geometric scattering, fragmentation, and land-use composition. Additionally, during the period investigated, density increased more in sprawl clusters than in compact clusters, 17.6% vs. 12.3% (Table 4). This finding points to the uniqueness and complexity of the urban sprawl phenomenon. Hence, as opposed to the accepted assumption in many studies (e.g., Torrens & Alberti, 2000), urban sprawl in not necessarily expressed in decreasing tendency in density with time.

In order to illustrate the advantage of using the integrated sprawl index, land-use maps for six different settlements are presented in Figure 4. The maps serve as examples of the diversity of



	Compact Pattern			Sprawl Pattern		
Varible	Bat Yam	Ramla	Bet She'an	Jerusalem	Pardes Hanna	Bet Shemesh
Integrated Sprawl Index	0	129.6	106.8	432.7	392	366.3
Population size (000)	133.9	62.8	15.9	680.4	28.8	53.4
Built-up area (sq/km)	7.6	8.6	4.8	51.1	8.5	7.6
Gross population density	17,600	7,600	3,300	10,500	3,400	7,000
Simple Sprawl Index (SI)	1.07	0.87	1.02	0.85	0.67	0.54

Figure 4: Six Examples of Land-Use Maps of Cities in t_1

urban settlements in our sample and of the level of complexity of the sprawl phenomenon. Three of the settlements present the compact pattern of the built-up area and were classified in cluster 1 (t_1), based on our integrated sprawl index. The other three examples present a sprawl pattern and belong to cluster 4 (t_1). Each of the two groups contains large and medium-size cities, as well as small towns, based on population size or the size of the built-up area.

Bet She'an is an example of small town with a low population density that, at the same time exhibits a compact pattern. An opposite example is Jerusalem, the largest city in Israel, which has a relatively high population density but presents a sprawl pattern. However, the most valuable finding is the comparison between the classification result based on the integrated sprawl index developed in this study and the classification that would have resulted from employing the popular Sprawl Index (SI) used in many other studies (e.g., Weitz, 2000; Hadly, 2000). Towns like Bat Yam and Bet She'an that definitely present compact patterns (in both configuration and composition dimensions) are sprawling according to the Simple Sprawl Index (SI=1.07 and 1.02 respectively). The reason is that Bat-Yam is an aging city with a declining built-up area that has been losing its residents. Therefore, its built-up area's growth rate is higher than its population growth rate, leading to SI > 1 -- sprawl pattern. An opposite example is presented by Jerusalem and Pardes-Hanna, which definitely present sprawling patterns based on the integrated sprawl index, but should be classified as compact according to the SI, with a value < 1 (0.85 and 0.67, respectively). These two settlements benefited from high immigration rates which led to a population growth rate higher than the built-up area growth rate. Our findings strengthen the assumption suggested in recent studies (Torrens & Alberti, 2000; Galster et al., 2001; Malpezzi & Wen-Kai, 2001), that sprawl is rather the description of a relative condition than a fixed, measurable category.

5.3 Sprawl Dimensions

Our last examination was performed on the two sprawl dimensions: configuration and composition. The purpose was to see whether these two dimensions are interlinked and to assess their contribution to the general level of sprawl and sprawl change over time.

As previously mentioned, Israeli urban settlements became more compact over time. By examining each sprawl dimension, we found that the configuration score decreased and the composition score slightly increased.[10] This means that settlements took on a more compact configuration (denser, more regular, and less scattered), but also a more sprawling, less mixed, land-use composition. This finding accords with the earlier findings on each of the sprawl measures.

Urban sprawl was found to be a multidimensional phenomenon as illustrated in the 3-dimension diagram in Figure 5. This diagram presents the value of the integrated sprawl index of every settlement as a function of the two separate sprawl dimensions, configuration and composition. As can be seen, some settlements demonstrate either as sprawling or non-sprawling pattern in both dimensions (Bat-Yam versus Qiryat Tiv'on), while other settlements show a level of sprawl affected by one of the sprawl dimension (Bene-Beraq versus Be'er Ya'aqov).

We also found that most of the settlements present a sprawl or compact form based on both dimensions. With respect to the change over time, the configuration dimension was found to

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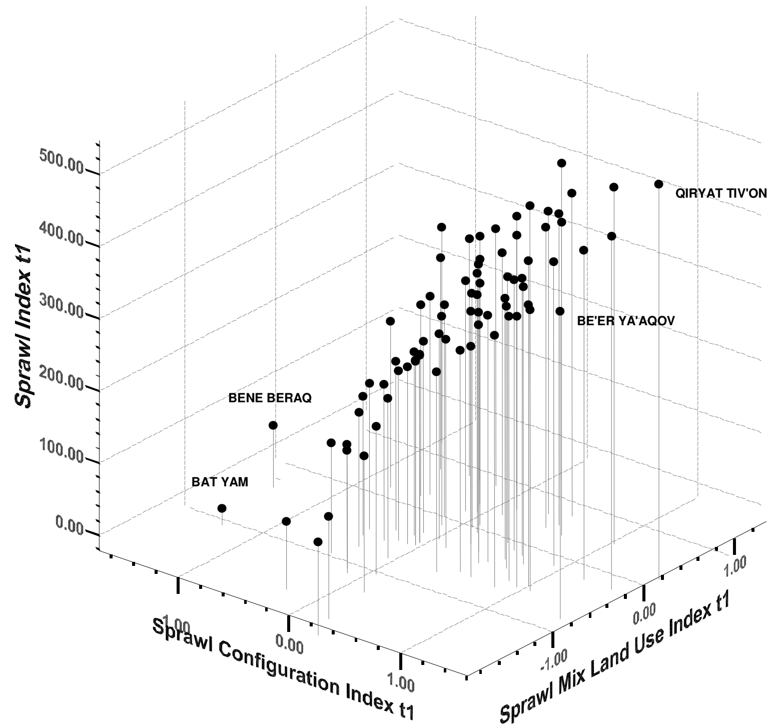
[10] Average configuration score in t_0 was 0.233, and 0 in t_1, with a standard deviation of 0.587; average composition score in t_0 was -0.063, and 0 in t_1, with a standard deviation of 0.599.

be more dominant through its impact on the change of the integrated sprawl index value than the composition dimension. In 41% of the settlements, the level of sprawl changed over time (positively or negatively) as a result of the configuration dimension; in 40% of the settlements, the change resulted from both dimensions. However, the change was brought about by the composition dimension in only 19% of the settlements.

The configuration dimension is linked to accelerated urban growth and increased land consumption, whereas the composition dimension is more linked to moderate growth rate and moderate land consumption. Thus, sprawl that resulted from a scattered, less dense configuration of the built-up area is more responsible for the waste of land than is sprawl that emanated from a homogeneous land-use pattern. This finding leads to the hypothesis that different sprawl patterns have different impacts on the urban form.



	Ranking score			
Settlement	Configuration Dimension	Composition Dimension	Integrated Sprawl Index	Sprawl Pattern
Bat-Yam	2	7	1	Compact in 2 dimensions
Qiryat Tiv'on	78	55	78	Sprawl in 2 dimension
Bene-Beraq	1	36	2	Compact in configuration dimension
Be'er Ya'aqov	77	10	70	Sprawl in configuration dimension

Figure 5: 3-Dimesion Diagram of Ranking Urban Settlements, According to Level of Sprawl

6. Conclusions

Urban sprawl is still a controversial issue among scholars, who argue over its impact as well as the way it should be measured. Hence, employing public policy in order to restrain the phenomenon is hampered, in particular, by the lack of empirical evidence. This lack affects the ability to convince the authorities to adopt such policies. Questions about exactly what sprawl is, how it affects urban environment, and how it should be measured remain unanswered.

Efforts have been undertaken recently to deal with these issues. This study focused on the measurable question: How can the various aspects and characteristics of sprawl be measured and what are the indices that should be implemented empirically in a unit of investigation at the town-scale level. In the past, most scholars tended to simplify the phenomenon of sprawl by defining it through one major index; e.g., density, density gradient, or a "sprawl index" expressing the ratio between built-up area growth rate and population growth rate. More and more studies have been examining the complexity of sprawl using various numbers of measures. The present study introduced 13 measures of sprawl that were implemented on land-use data gathered from 78 urban settlements in Israel. It divided the suggested measures into five major groups and two dimensions: configuration and composition. An integrated sprawl index was weighted by factor analysis and then used to compare sprawl levels among settlements and to assess the dynamics of sprawl over a time period of two decades.

The integrated sprawl index introduced in this paper is an unusual combination, making use of sprawl measures from different disciplines: urban studies, fractal geometry, and ecological research. We note, however, that there are some measures that are more effective in measuring sprawl on a municipal scale (e.g., density, shape/fractal, residential, commercial, and industrial land-use composition) and other measures that are less effective or less relevant (e.g., leapfrog, MPS, other built-up land uses). The latter group seems to be more effective in measuring sprawl on a regional or metropolitan scale.

Not all sprawl measures that were implemented in this study were found to be highly correlated with each other, and we realized that various measures do not substitute for each other. Settlements were found to be sprawling or compact by either one dimension or both dimensions (configuration and/or composition). The various sprawl measures used in this study show clearly that urban sprawl is a multidimensional phenomenon that cannot simply be described by only one or two popular measures (e.g., density or growth rates), as often is done in other urban studies. It is, rather, a complex phenomenon that should be described and quantified by a combination of several measures. Each group of measures represents different features or dimensions of this phenomenon and does not necessarily depend on other dimensions.

Urban land-use composition is less heterogeneous than is open land-use composition because of the dominance of residential uses within the urban built-up area. Hence, a residential land-use measure represents well the urban land-use composition, obviating the need to compute all other land-use percentage. Further development of the sprawl mix of land-use measures is still needed; for example, the level of segregation and accessibility between different land uses.

The results of this study show that most urban settlements in Israel have become less sprawling over the past two decades. We especially found differences between the two dimensions of sprawl and their effect on the urban landscape pattern. The sample of settlements investigated became more compact in its configuration perspective, but more sprawling in its composition perspective. Since urban sprawl appears to be a complex, multi-dimensional phenomenon, we hypothesize that its implications are also complex, and they probably emerge from different urban patterns of development. Apparently, this complexity is linked to the disagreements that exist between scholars and planners on this issue. Our finding implies that different sprawl patterns have diverse implications for urban form that should be investigated. Some settlements, especially quasi-rural ones, were found to be more sprawling than others. This fact implies that sprawl rates may be higher in rural settlements than in urban settlements. Therefore, we highly recommended continuing the investigation of rural sectors, as this might be more relevant to sprawl and its impacts on land consumption.

Higher sprawl rates were found to be significantly correlated with higher population and higher land-consumption growth rates. This finding implies a higher, consumer preference for residing in more sprawling patterns. A definite conclusion on this matter requires further investigation of consumer preferences and the alleged positive impacts of sprawling patterns perceived by consumers. Assuming sprawling settlements are more attractive to new residents and based on the lack of available land in Israel, we find attempts to regulate and restrain sprawl in Israel to be highly justified.

Annex A: Sprawl Measures that Were Operationalized in this Research

Note: Each measure was operationalized both for t_0 (mid- 1980s) and for t_1 (year 2002).

Nomenclature

Let:

i = a particular urban settlement in the research sample

j = type of land use[1] (j=1..10): j=1 residential[2]; j=2 industry; j=3 institutions; j=4 mixed land use (CBD); j=5 tourism and recreation; j=6 special uses; j=7 malls[3]; j=8 open space; j=9 non-used land; j=10 agricultural land.

P_i = number of residents in urban settlement i

A_i = central built-up area of urban settlement i

UA_i = urban built-up area of settlement i, including land-uses 1, 2, 3, 4, 5, 6_{in}, 7_{in}, 8_{in}, 9_{in}

RA_i = residential area of settlement i (land-use no. 1)

L_i = perimeter of central built-up area of settlement i

$Aout_i$ = leapfrog areas in settlement i, including land-use categories: $j_{out\ 1\text{-}7}$, except for land-use category j_{out6}[4]

$RAout_i$ = residential area outside the central built-up area of settlement i

a_{ij} = area of land-use j in urban settlement i (j=1…10)

n_{ij} = number of polygons of land-use j in urban settlement i (j=1…10)[5]

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1. J refers to each of the specified land-use categories within a settlement's jurisdiction. J_{in} refers only to land-use categories located within the central built-up area, while J_{out} only to those located outside the central built-up area.

2. This category includes the residential parcels and the attached neighborhood infrastructure (public institutions, neighborhood civic centers, open spaces, public gardens, and local roads).

3. In t_1 land-use 2 (industry) was summed up with land-use 7 (malls), unless specified otherwise. In t_0 (mid-1980s), there were no malls in Israel, except for the city of Ramat-Gan; hence, land-use 7 is irrelevant in that time period.

4. Special areas outside the central built-up area are usually not functionally correlated with the urban settlement, such as cemeteries, airports, military bases, etc. Therefore, they were not included in the urban-sprawl measures, unless otherwise specified.

5. Minimum size of the polygon of specific land-use j was 3 hectares for all uses, except for non-used land, for which the minimal size of the polygon was 5 hectares.

Given this nomenclature, we defined each one of the sprawl measures operationalized in this study as follows:

Density Indices

Gross density: $D_{gi} = \frac{P_i}{UA_i}$

Net density: $D_{ni} = \frac{P_i}{RA_i}$

Impact on sprawl: negative (higher density means lower sprawl).

Irregularity of Shape Indices[6]

Shape Index: $SH_i = \frac{L_i}{2\sqrt{\pi A_i}}$

Fractal Dimension: $F_i = \frac{2 \log L_i}{\log A_i}$

Impact on sprawl: positive.

Fragmentation Indices

Gross Leapfrog Index: $LFI_{gi} = \frac{Aout_i}{UA_i}$

Net Leapfrog Index: $LFI_{ni} = \frac{RAout_i}{RA_i}$

Impact on sprawl: positive.

Mean Patch Size: $MPS_{ij} = \sum_{j=1}^{7} \frac{a_{ij}}{n_{ij}}$

Impact on sprawl: negative.

6. In this group of indices, the units of measurements were m for L_i and m^2 for A_i.

Land-Use Composition Indices

Six land-use categories were used to identify the land-use composition of the built-up area of settlement i. The measures were calculated as a percentage of land-use j from the entire urban built-up area (UA_i).

$$LU_{ij} = \frac{a_{ij}}{UA_i} \qquad j = 1...6$$

Impact on sprawl: residential use -- positive; all other built-up uses -- negative.

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