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Methodology matters: measuring urban spatial development using alternative methods

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Abstract. The effectiveness of policies implemented to prevent urban sprawl has been a contentious issue among scholars and practitioners for at least two decades. While disputes range from the ideological to the empirical, regardless of the subject of dispute, participants must bring forth reliable data to buttress their claims. In this study we discuss several sources of complexity inherent in measuring sprawl. We then exhibit how methodological decisions can lead to disparate results regarding the quantification and characterization of sprawl. We do so by employing three GIS-based methods for quantifying the amount and defining the configuration of land-cover change from open to built space in a 350 km^2 area in central Israel over a five-year period. We then calculate values for a variety of spatial indices commonly associated with urban sprawl. Our results reveal that some urban growth patterns are so robust that multiple methods and indices yield similar results and thus lead to similar conclusions. However, we also note that many divergent and even contradictory results are produced depending on the measurement method used and the index selection.

Keywords: urban sprawl, spatial analysis, sprawl indices, landscape fragmentation, urban form, GIS

1 Introduction

Urban sprawl has important implications for environmental quality, ecology, and socio-economic equity (Bruegmann, 2005; Ewing, 2008; Ewing et al, 2002). Since sprawl is considered by most (though not all) to be an undesirable pattern of spatial development, curtailing sprawl is the goal of numerous urban and regional planning and policy initiatives around the world (Bengston et al, 2004; Bruekner, 2000; European Environment Agency, 2006, page 60; Frenkel, 2004; Van Rij et al, 2008).

Yet, such policies face strong scrutiny and criticism due to the contentious question of whether sprawl is a desirable and/or unavoidable phenomenon and due to the debate regarding the proper role of government in addressing the issue (Gordon and Richardson, 1997; 2000; Mitchell, 1998; Neuman, 2005). Because of this and the desire to implement effective policies, scholars and practitioners must have accurate and reliable data on the spatial extent and configuration of land uses and development.

In order to assess where and how urban sprawl is occurring, urban spatial growth must be carefully and constantly monitored, measured, and characterized. The process of compiling such data seems intuitively simple, but we suggest it is fraught with complexity and that such complexity leads to great dispute. Measuring sprawl is challenged by at least three layers of complexity: disagreement regarding the precise definition of sprawl, the choice of methods for quantifying built space (the baseline data on which sprawl assessments are made), and

the choice of indices used to characterize and measure sprawl. Choices made by researchers at each point of analysis can affect conclusions regarding whether or not sprawl is occurring.

The objective of this study is to investigate how methodology can affect final conclusions of urban sprawl assessments. We employ three methods for estimating the area and spatial distribution of built space in a mixed urban–suburban–rural landscape, and then apply a diversity of indices to the results in order to characterize patterns and rates of development. We show how some urban spatial development patterns are so robust that they are recorded similarly regardless of measurement or characterization method. On the other hand, some sprawl indices yield different and even opposite results due to their sensitivity to both the extent and the spatial configuration of development, both of which are sensitive to the method selected for quantifying built space.

We begin by describing the concept of urban sprawl and providing an overview of how it has been measured. We present our three assessment methods for measuring built space, and nine indices we selected to characterize sprawl. We present the values of the indices derived from the three different measurement methods. In order to gain insights regarding the implications of changes of the spatial extent and configuration of built space on index values in general (beyond our particular case study), we conduct a sensitivity analysis of six indicators using a set of artificial urban spatial development patterns with predefined values for the amount of urban cover (ie, the extent) and the degree of aggregation of built space (ie, the configuration). We conclude with a discussion of the implications of the results of each of the three spatial analysis methods and the values of spatial indices on conclusions regarding the presence or absence of sprawl in this case study and in urban sprawl research in general.

2 Background

The term 'urban sprawl' is used as a descriptive, yet generic, term to describe a variety of urban development forms that share relatively low density of buildings and population as a common trait (Burchell et al, 1998; Ewing et al, 2002; Torrens, 2008; Tsai, 2005). Yet, this definition is too vague for policy purposes and there is wide disagreement regarding a more precise definition (Chin, 2002; Galster et al, 2001; Wolman et al, 2005). Cutsinger and Galster (2006) suggest that a definition of sprawl cannot be simplified to a single 'syndrome', but rather must be dealt with as one or more of several potentially noncorrelating phenomena. This is at least partly understood when considering that sprawl can have different definitions at different spatial scales—for instance, at the scale of a single urban settlement or at the scale of a region of multiple settlements. Ewing (2008) suggests that sprawl is broadly definable as 'undesirable' scattered development, leapfrog development, strip or ribbon development, or continuous low-density development. However, he qualifies that sprawl is a matter of degree, and that one or more of three dimensions (density, land use, and time) may govern whether an urban development pattern is problematic.

Several additional syntheses of sprawl definitions exist in the literature (Burchell et al, 1998; Chin, 2002; Frenkel and Ashkenazi, 2008; Galster et al, 2001; Torrens, 2008). According to these, sprawl has been defined in three ways: (1) as a spatial development pattern; (2) as spatial development that leads to undesirable social, economic, and/or ecological consequences; and (3) as particular socioeconomic trends that lead to particular urban spatial development patterns. In this research, we focus on the first type of definition: a pattern of urban spatial development which includes one or more of the archetypes: scattered, leapfrog, ribbon/strip, and/or low-density development.[1]

[1] We retain this definition despite the fact that we concur with Ewing (2008), when he writes that "it is the impacts of development that render development patterns undesirable, not the patterns themselves." The purpose of this paper is to point out the complexities in defining pattern, while assuming that in many cases pattern determines process.

It is important to note that sprawl is perceived more successfully as a relative, rather than absolute, phenomenon (Johnson, 2001; Pendall, 1999). Further, sprawl can be both a process and a state. Quantifying the relative nature of sprawl requires comparative research either across study sites, to assess what urban areas are more 'sprawled' than others, or over time, to assess whether changes in urban spatial patterns at a given site are increasingly sprawled over time (Frenkel and Ashkenazi, 2008; Galster et al, 2001; Torrens and Alberti, 2000).

Spatial analyses of urban sprawl are confounded by at least three layers of complexity. First is the problem of unified definition, as noted above. Even when a spatial pattern definition is agreed upon, the debate then shifts to whether or not sprawl is a desirable phenomenon (Ewing, 1997; 2008; Gordon and Richardson, 1997; 2000). Second, both the selection of primary data (eg, maps, orthophotos, or satellite imagery) and the methods to extract built space estimates may influence the final outcome of sprawl assessment (Orenstein et al, 2011; Schneider et al, 2009; Torrens, 2008). Third, the choice of sprawl indices may also have an affect on final assessments of sprawl (Frenkel and Ashkenazi, 2008; Torrens, 2008). Each of the wide variety of indices captures different characteristics of spatial development (Frenkel and Ashkenazi, 2008; Hasse, 2004; Torrens, 2008) and contradictory results may be produced depending on the index employed. Further, indices differ with regard to their sensitivity to types of spatial patterns and their change over time (Gustafson and Parker, 1992; Li and Wu, 2004).

We posit that many of the classic debates around urban sprawl arise from either an ideological split regarding how a city should develop (eg, Ewing, 1997; 2008; Gordon and Richardson, 1997; 2000), or due to methodological differences that produce contrary results in different research (eg, Kline, 2000; Nelson, 1999; 2000). We return to this theme in the discussion section.

3 Research questions

In this work we address two sources of complexity facing sprawl researchers, as noted above—those attributed to the selection of methods for quantifying built space and to the selection of sprawl indices. We assume that we have circumvented the first source of complexity by explicitly stating our definition of sprawl for our particular study site rather than using the generic term and assuming a broad consensus on its definition. So, we consider how the application of different methods for quantifying and characterizing the amount and spatial distribution of built land in a given area can yield different results and confound assessments of whether or not sprawl is occurring. Our specific research questions are:

(1) How does selection of methods by which to measure the extent of built space affect the quantitative estimate of built space and its spatial distribution?

(2) How does selection of sprawl measures affect assessment about whether sprawl is occurring, and, if so, where and when?

(3) Are spatial development trends in our case study robust enough to produce consistent results across quantification methods and sprawl indices?

4 Research methods

4.1 Study site

We study Israel's Sharon subdistrict, which is part of the Tel Aviv Metropolitan region. The Sharon subdistrict is situated along the Mediterranean coast to the north of the city of Tel Aviv (figure 1). It covers 348 km^2, constituting 1.6% of the total area of Israel. In 2006 a total of 363 300 people resided within these borders, constituting 5.2% of the country's population. The population growth rate during the last decade was 31.6%, or 2.8% annually, in comparison with the national average of 2.2%. Population density in the region was 1044 residents per km^2, in comparison with the national population density of 323 residents per km^2 (Central Bureau of Statistics of Israel, 2007).

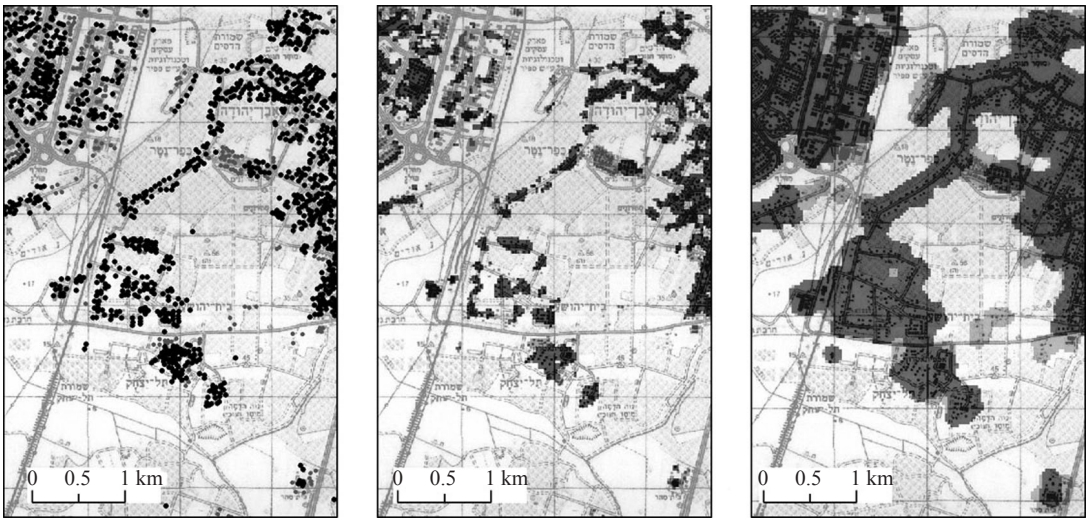
Figure 1. Sharon subdistrict.

The topography of the Sharon subdistrict is moderate, with elevations ranging from sea level to 80 m. Land use is characterized by a high percentage of cultivated agriculture and by low-density to medium-density rural and exurban Jewish communities, Arab towns, and the coastal city of Netanya. The goal of protecting open space is particularly challenging in the Sharon subdistrict, where unique ecosystem types, including coastal sand dunes and riparian ecosystems, overlap with high-demand real estate and prime agricultural land (Achiron-Frumkin et al, 2003). While the ecological function of agricultural land is different from natural areas (ie, open land not intentionally manipulated or degraded), it serves numerous important functions in the provision of ecosystem services (Swinton et al, 2007). These include open space for water infiltration and groundwater recharge, cultural landscapes, habitat for some bird and insect species, 'green lungs' separating contiguous urban development, carbon and pollution 'sinks', and, of course, food provision (Swinton et al, 2007). The combination of high demand for residential development and ecologically valuable habitats makes the Sharon subdistrict an ideal site to examine and characterize urban spatial development.

4.2 Measuring built space

Three methods were employed to quantify built space in the research area. We entitle these as: (1) 'point', (2) 'DBScan', and (3) 'polygons'. Importantly, each of the methods has been employed previously by researchers for both academic studies and practical applications.

The first and second methods both use scanned 1:50 000 scale survey maps produced by the Survey of Israel. The Sharon subdistrict is contained in four map series that are each updated at irregular intervals. For this research, maps were aggregated for 1999 and 2003, such that the most recent maps up to those years were used. Built structures on the maps were digitized as points [figure 2(a)]. One point was placed manually on each building with the exception of buildings with a large footprint, which were marked with two or more points (the footprint of the built area was considered in the next step of data preparation discussed below). Other human structures, such as roads, cemeteries, and parking lots were not considered as built. [For a thorough review of the method, see Orenstein and Hamburg (2010) and Orenstein et al (2011).] At this point, the methods for the first and second analyses diverge.



(a) (b) (c)

Figure 2. Method for digitizing structures utilized in 'points' and 'DBScan' methods and the resultant built space map: (a) digitizing all structures with a single point; (b) creating a density grid for built space; (c) utilizing the DBScan method (see text).

For the first analysis ('points'), the point vector files were converted into structure-density raster grids (using ArcGIS, spatial analyst extension, density function) with 30 m resolution using a 30 m search radius and a kernel density function. Kernel density function weights the centre of the search radius more heavily than the edges, producing a smoother density distribution. A 30 m resolution was wide enough to ensure that the spatial footprint of large buildings would be included as built. A pixel was then defined as built if it contained at least one structure or was within 30 m of a structure (thus with a pixel threshold value $\geqslant 1$). We applied a smoothing filter using a 3×3 pixel moving window to reclassify pixels according to the majority pixel value within the window so lone structures within an open matrix would not cause the pixel to be defined as built, nor would small open patches in the built matrix cause the pixel to be defined as open [figure 2(b)].

The second quantification method ['DBScan', see figure 2(c)] relies on the same point vector file for structures as the first method, but a mathematical algorithm (density-based spatial clustering of applications with noise or DBScan) is employed to assign structures automatically to a given cluster of built space (Borah and Bhattacharyya, 2004; Duan et al, 2007; Ester et al, 1996). The algorithm places points (structures) into clusters according to their respective densities and proximity to one another, taking into account two parameters: the minimum number of points that constitute a cluster (MinPts, determined by the user), and the maximum distance at which a point will be considered reachable from other points (ε).

Reachability for point p is thus defined when p is within the maximum distance of an adjoining point; a cluster is created when a minimum number of points are reachable from one another. The DBScan algorithm is as follows (Ester et al, 1996):

(1) Arbitrarily select a point p from the point vector file;

(2) Retrieve all points density reachable from p with respect to ε and MinPts. In the current research, MinPts = 5 and ε = 300 m (see below);

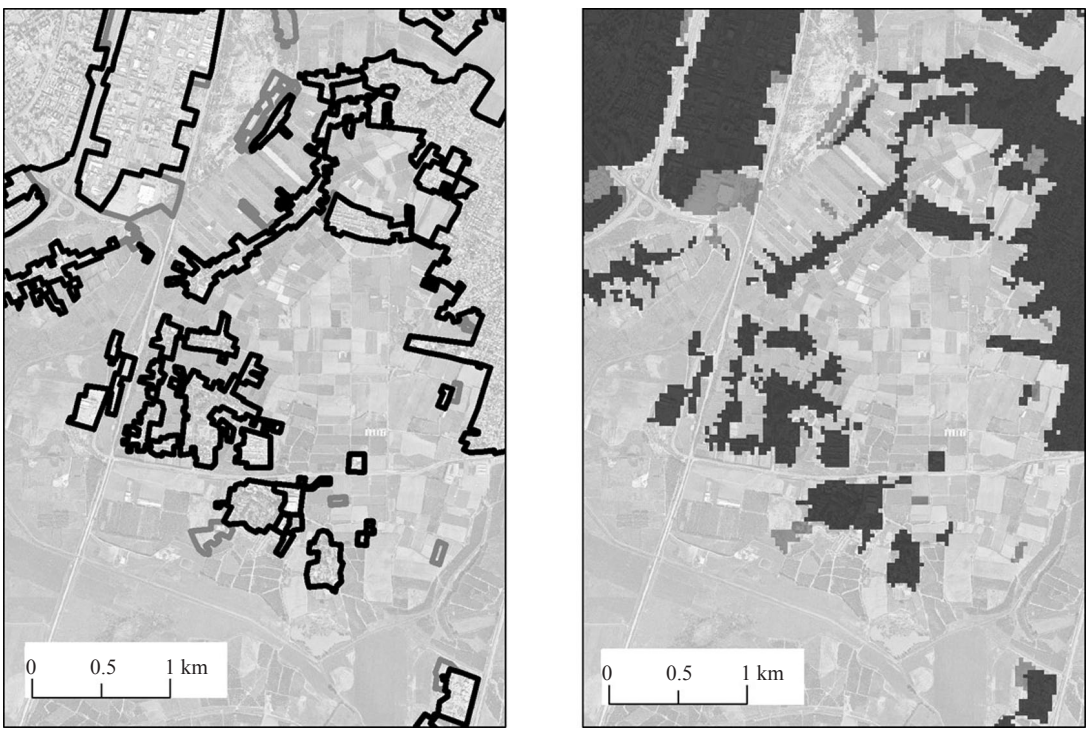
(3) If p is a core point, a cluster is formed;

(4) If p is a border point, no points are density reachable from p and DBScan moves to analyzing the next p;

(5) Continue the process until all points have been processed, thereby defining the number of clusters.

In order to determine the optimal distance parameter, ε, we ran DBScan in iterations, using step increments of 25 m radius to establish the optimal clustering of points (this occurs when the number of clusters in the area of analysis ceases to change with increasing increments of 25 m); this process yielded 300 m as the optimal value for ε. To reduce the amount of open space in the cluster, a 150 m buffer area was added to each point to form final polygon clusters, and then the buffer area around each polygon was reduced by 50 m around its perimeter. The polygons, defined as the area of built space, were transformed into a raster file of 30 m^2 pixels for further analysis.

The third assessment method to quantify built space ('polygons', figure 3) uses high resolution orthophotos for digitizing polygons of user-defined built space. A 1998 built space map of the entire country was produced using this method during the preparation of National Outline Plan (NOP) 35. A 2003 map was prepared for the final draft of the NOP (Cohen et al, 2010). Built space in this methodology is defined as land covered by human-built structures including residential, commercial, industrial, and institutional structures, as well as other human manipulations including quarries, as interpreted from orthophotos



(a) (b)

Figure 3. Method for digitizing built space (a), and resultant built space map following rasterization (b).

by technicians [figure 3(a)]. The resultant maps' scale was 1:4000. Some open space was knowingly included in built space polygons, including open space between buildings (public parks within built areas, yards, roads, cemeteries), so that the built space would be continuous for urban areas. Large natural areas within the urban fabric and public open spaces at the boundaries of the built areas were not included in the built space polygon. Isolated built areas that were less than 1.0 ha in area were not included as built space. The built space polygon file was transformed into a raster file, similar to the first two methods, for further analysis [figure 3(b)].

4.3 Indices to characterize sprawl

Because urban sprawl has implications for both urban development and open space preservation, the spatial indices we employ to measure sprawl are drawn from both urban planning and conservation biology. There are tens of potential sprawl measures to choose from (Ewing et al, 2002; Frenkel and Ashkenazi, 2008; McGarigal et al, 2002; Torrens, 2008). We selected indices on the basis of two criteria. First, we sought a representative sampling of the broad variety of types of measures which would capture the multiple characteristics of urban spatial development. Second, we desired measures that would either characterize urban spatial development in a way that would be easily understandable for researchers and practitioners or provide important information regarding the ecological implications of development on remaining open spaces. The following nine indices were selected (equations for indices 3–9 are found in appendix A):

- Gross population density (index 1). This index is the number of people divided by the amount of built land in a given area. A decline in gross population density implies an increase in sprawl.
- Sprawl index (index 2). This is the percentage change in the amount of built space divided by the percentage change in population size. A value greater than one implies that built space is growing proportionally more than population, thereby implying sprawl (Hadly, 2000). In the event of negative population growth, the index value also becomes negative, suggesting development of land in the absence of population growth.
- Number of patches (indices 3 and 4). Built and open spaces can be considered to be functional 'patches' in that the ecological dynamics of a given patch type are more similar to other patches of its type than to those of other patch types (Gustafson, 1998). An increasing number of built patches implies scattered, noncontiguous urban development. An increasing number of open space patches implies greater landscape fragmentation and more edge effect due to proximity to developed areas, both considered to have negative effects on biodiversity and ecosystem function (Hansen et al, 2005). The number of patches was quantified using FragStats software. Patches are defined as groups of contiguous pixels as defined by the 4-neighbor rule. Contiguous pixels are considered as touching if they share a side, but not a corner (McGarigal et al, 2002).
- Total edge (index 5). A greater amount of edge between patch types implies irregularity of form. For urban planning this is interpreted as development that is not compact (eg, not circular). Ecologically, this is interpreted as having greater potential for open spaces to be subject to human disturbance (Meffe and Carroll, 1994). An increasing amount of edge implies an increasingly fragmented and irregular landscape. The amount of edge, measured in meters, was quantified using FragStats as the total edge length of all patches of a given type. Because we defined only two patch types, total edge for built space equals total edge for open space.
- Mean shape index for built area (index 6). The shape index is the total perimeter of the patch divided by the minimum perimeter possible (eg, for a circle of the same area). The value is one for a perfect circle implying compactness, and becomes larger with increasing irregularity of shape (McGarigal et al, 2002).

● Total core area and mean core area for open space patches (indices 7 and 8). While total open area measures how much of the landscape is not built, total core area for open space patches subtracts open space that is within a user-defined buffer from built space. Size of a preserved ecological unit has important ramifications for the long-term conservation of species and healthy ecosystem function and the functional size of a reserve is smaller than its actual size due to edge effect (Meffe and Carroll, 1994). We used a 50 m buffer to define the core area of open space.[2] The value of the core area is affected by both the size and the shape of the patch, as well as the depth of the user-defined buffer zone.

● Connectance of open space patches (index 9). In addition to individual patch geometry, the aggregate distribution patterns of patches is posited to affect ecological function at the landscape scale (Gustafson, 1998). Fragmentation of open space is considered to impair ecosystem function and lead to loss of species (Hansen et al, 2005).[3] This index measures the functional connectedness between patches using a user-defined threshold after which patches are considered to be isolated from one another (McGarigal et al, 2002). We used a 100 m threshold to calculate connectance.[4]

4.4 Scale of analysis

Another central theme in spatial analyses of sprawl, and an additional level of complexity, is scale of analysis. Different dynamics occur and are able to be measured at different levels of spatial aggregation (Clifton et al, 2008; Orenstein and Hamburg, 2010; Tsai, 2005). Further, certain sprawl indices have meaning only at specific scales of analysis (Frenkel and Orenstein, 2011). In this research, selected indices are applied at one or two scales of analysis. The first is the aggregate scale that includes the entire Sharon subdistrict. At this scale of analysis we provide values for all nine indices listed above.

At the second scale of analysis we disaggregate the subdistrict into four locality types, each of which is defined by specific community types and their typical and distinct development patterns that distinguish them from one another, including (1) city (Netanya), (2) Arab towns, (3) local councils (predominantly Jewish suburban and exurban communities), and (4) regional councils (Jewish rural communities). The population size for 1997 and 2003 for each locality type is found in table 1. At this scale of analysis, interpreting values of the indices becomes difficult because in reality the values would be affected by spatial development in adjoining localities.

Table 1. Population and growth for 1997 and 2003 in the Sharon subdistrict and in localities therein (source: Central Bureau of Statistics of Israel, 2007).

Locality type	1997		2003		Rate of growth (%)
	population	%	population	%	
Core city (Netanya)	162 179	51.5	167 051	48.4	3.0
Arab towns	55 819	17.7	66 946	19.4	19.9
Local council (residential suburbs)	37 960	12.1	56 762	16.5	49.4
Regional councils (rural settlements)	59 088	18.8	54 204	15.7	–8.3
Total for Sharon subdistrict	315 076	100.0	344 963	100.0	9.5

[2] We chose a 50 m buffer as a reasonable mid-range distance where ecological effects of human development may be felt on open space, including such effects as noise, light, and hunting by domesticated animals.

[3] But also see Fahrig (2003) for a more equivocal view of the ecological implications of fragmentation.

[4] The 100 m threshold was to provide a sample value representative of the ability of animal and plant species to pass through built areas; of course this number would vary widely depending on the species or taxa in question (as well as the type of human development dividing the open space patches and many other variables).

Thus, computing the values of the indices in isolation from neighboring localities would produce misleading results. We chose three indices that would still provide interpretable results (total edge, mean shape index for built area, and total open space core area), along with two indices that are not affected by this problem (gross population density and sprawl index).

5 Results

The built space maps generated by the three GIS methods for quantifying built space are shown in figure 4. The total amount of built space and the amount of built space as a proportion of the entire Sharon subdistrict in 1999 (1998 for the polygons method) and 2003 as assessed

Figure 4. The final built area maps produced by the (a) points; (b) DBScan; (c) polygons methods.

Table 2. Total amount of built space by locality as estimated by the three methods.

Locality	Method	1999[a]		2003		Rate of growth (%)
		built space (ha)	% of total area	built space (ha)	% of total area	
Netanya	points	859	28.3	943	31.0	9.7
	DBScan	1 851	60.9	1 991	65.6	7.6
	polygons	1 396	46.0	1 500	49.4	7.5
Arab towns	points	506	12.8	582	14.8	15.1
	DBScan	1 361	34.6	1 651	42.0	21.4
	polygons	1 069	27.2	1 113	28.3	4.1
Local councils	points	574	12.5	690	15.0	20.3
	DBScan	1 700	36.9	1 900	41.2	11.8
	polygons	1 029	22.3	1 117	24.3	8.6
Regional councils	points	1 814	7.7	2 065	8.8	13.9
	DBScan	6 079	25.9	6 735	28.7	10.8
	polygons	3 111	13.3	3 287	14.0	5.6
Subdistrict	points	3 755	10.7	4 284	12.2	14.1
	DBScan	11 002	31.4	12 289	35	11.7
	polygons	6 611	18.8	7 024	20	6.2

[a] 1998 for the polygons method.

by each method are shown in table 2. According to all three methods, the total amount of built space rose over the four-year period, although the initial estimates of total built space at each time and the proportional rise reveal large differences in results between the three methods.

The points method consistently yielded the smallest estimates of built space, sometimes only one third to one half of the estimate of the other methods. DBScan, by contrast, always provided the largest estimates of built space. This is, in part, a result of applying the algorithm to the entire region, rather than to each community individually, which produced a relatively large value of reachability between clusters of structures. The polygon method systematically estimates the smallest amount of growth of built space. Despite consistently small estimates of built space, the points method estimates the highest amount of growth of built space (with one exception, Arab towns, where DBScan provided the highest amount of growth of built space).

Population densities in 1999 (1998 for the polygons method) and 2003 are given in table 3. Population density, which is a direct function of total amount of built area, fell in the subdistrict according to the points and DBScan assessment method, and rose according to the polygons method. Changes in density for individual locality types (city, local councils, Arab towns, regional council) varied. In Netanya and the regional councils, all three methods yielded a decline in density; in local councils, all three yielded a rise in density. In the Arab towns, the results were mixed, with two methods (points and polygons) measuring a rise in density and the DBScan measuring a decline.

Table 4 displays the spatial index values in 1999 (1998 for the polygons method), and the relative change between that year and 2003. The proportional rise in built space in the region between 1999 (1998) and 2003 was 14.1%, 11.7%, and 6.2%, for points, DBScan, and polygons, respectively (table 2). Dividing these results by proportional change in population size (9.5%) yields the sprawl index value. Sprawl index values >1 (ie, sprawl) resulted from

Table 3. Population density.

Locality	Method	Population density (persons/ha built space)		Rate of change (%)
		1999[a]	2003	
Netanya	points	188.7	177.1	−6.1
	DBScan	87.6	83.9	−4.2
	polygons	116.1	111.3	−4.1
Arab towns	points	110.3	115.0	4.3
	DBScan	41.0	40.5	−1.2
	polygons	52.2	60.1	15.1
Local councils	points	66.1	82.2	24.4
	DBScan	22.3	29.9	34.1
	polygons	36.9	50.8	37.7
Regional councils	points	32.6	26.2	−19.6
	DBScan	9.7	8.0	−17.5
	polygons	19.0	16.5	−13.2
Subdistrict	points	83.9	80.5	−4.1
	DBScan	28.6	28.1	−1.7
	polygons	47.6	49.1	3.2

[a] 1998 for the polygons method.

the points and DBScan methods, and a value <1 (ie, compact) resulted from the polygons method (table 4). Note that the points method estimated a significantly higher proportional rise in built space than the DBScan method even though the former estimates only one-third the amount of built space of the latter method.

With regard to the spatial patterns of urban development (change in number of open patches, number of built patches, total edge, total core open space, and mean open patch core area), the results among the methods are consistent with regard to directionality, but vary with regard to the magnitude of change. The number of open and built patches rose, the total amount of edge rose, and the total amount of core open space and the mean open patch core area fell. All these indices suggest a higher degree of landscape shape irregularity as measured by all assessment methods, although the magnitude of change differs widely between methods as can be seen by comparing both absolute values and the amount of relative change between years.

Two spatial indices yielded more ambiguous results: the change in mean shape index for built area rose according to the points method, and fell according to the two other methods. Connectance of open space patches rose for the DBScan method, but fell for the other two methods.

At the scale of localities, the results were mixed. In the regional councils, population density declined, and the sprawl indices suggested sprawl was occurring, regardless of method. Edge was increasing, and total open core area was declining (ie, sprawl) according to all methods. The change in mean shape index for built area rose for two of the methods (points and polygons) but fell according to the third (DBScan).

In the local councils, population density rose in all cases, and the sprawl index suggested compact development rather than sprawl (an important finding to be discussed further in the following section). Spatial development pattern indices were ambiguous. There was

Table 4. Sprawl measures according to three methods for the Sharon subdistrict and locality groups (italicized numbers are those that suggest sprawl).

Index	Quantitative meaning	Method	Sharon subdistrict		Regional councils		Local councils		Arab towns		Netanya	
			absolute parameter in 1999[a]	change between 1999[a] and 2003	absolute parameter in 1999[a]	change between 1999[a] and 2003	absolute parameter in 1999[a]	change between 1999[a] and 2003	absolute parameter in 1999[a]	change between 1999[a] and 2003	absolute parameter in 1999[a]	Change between 1999[a] and 2003
Sprawl index (ratio)	When population growth and growth in built space are equal, index = 1. Values >1 or <0 infer sprawl	points		1.49		−1.68		0.41		0.76		3.24
		DBScan		1.23		−1.31		0.24		1.07		2.53
		polygons		0.66		−0.68		0.17		0.21		2.48
Change in number of open patches	Higher values infer more fragmented landscape	points	226	25.7								
		DBScan	53	20.8								
		polygons	35	48.6								
Change in number of built patches	Higher values infer more fragmented landscape	points	758	5.3								
		DBScan	88	11.4								
		polygons	275	17.1								
Change in total edge (m)	More edge infers higher irregularity in shape (and more sprawl). Less edge implies more compact shape	points	933 690	11.5	511 650	9.9	155 280	9.8	115 140	21.5	148 470	10.7
		DBScan	674 550	8.6	450 030	7.8	94 560	10.1	57 240	28.8	66 570	−5.5
		polygons	904 710	8.3	575 310	6.3	114 450	6.4	109 320	15.3	98 310	14.7
Change in mean shape index of built area (ratio)	1 implies optimal compactness; positive change implies sprawl	points	1.38	0.8	1.39	0.8	1.38	−0.3	1.35	−0.8	1.33	3.4
		DBScan	1.71	−2.5	1.58	−2.5	1.52	0.5	1.53	12.0	1.89	−16.5
		polygons	1.77	−3.1	1.73	0.4	1.53	−3.4	1.61	−5.3	1.51	−4.9
Change in total open core area (ha)	Not a sprawl measure, per se. 0 means no core open spaces	points	28 139	−2.9	19446	−2.0	3 287	−4.1	2 948	−5.0	1 637	−7.3
		DBScan	21 735	−6.7	15 527	−4.7	2 389	−8.9	2 279	−14.3	912	−13.8
		polygons	25 518	−2.4	18 110	−1.4	2 991	−3.5	2 432	−3.6	1 253	−11.1
Mean open patch core area (ha)	Not a sprawl measure, per se. From 0 to entire geographic area; lower numbers mean smaller patches	points	124.5	−22.7								
		DBScan	410.1	−22.7								
		polygons	729.1	−34.3								
Change in connectance	Percentage of the maximum potential connections between patches	points	0.80	−18.0								
		DBScan	1.23	4.5								
		polygons	5.21	−30.5								

[a] 1998 for the polygons method.

more edge, suggesting a higher degree of irregularity, and loss of open core area (ie, more sprawling), but with two of three methods, the mean shape index for built area declined slightly, suggesting almost no change.

In Arab towns, only one of the three methods, DBScan, suggested sprawl according to change in gross population density and the sprawl index, with the other two methods offering contrary evidence. While a greater degree of edge and a loss of open core area was measured in all three methods, according to change in mean shape index for built area, the same two methods (points, polygons) suggested increasing compactness, while the third (DBScan) suggested sprawl.

With regard to the city of Netanya, according to all three methods, gross population density was falling and the sprawl index was relatively high. Edge rose according to two methods (points and polygons) and fell according to the third (DBScan). Mean shape index for built area fell according to the DBScan and polygons methods (suggesting more compactness) and rose according to the points method.

6 Assessment of landscape indicators on neutral (randomly generated) landscape patterns

In order to test the sensitivity of the indices to changes in extent and configuration of urban spatial development we generated a set of neutral landscape patterns using QRule software (Gardner, 2011; McGarigal, 2012) and computed the values of the indices for these landscapes (appendix B). Two variables were controlled when generating the artificial patterns:

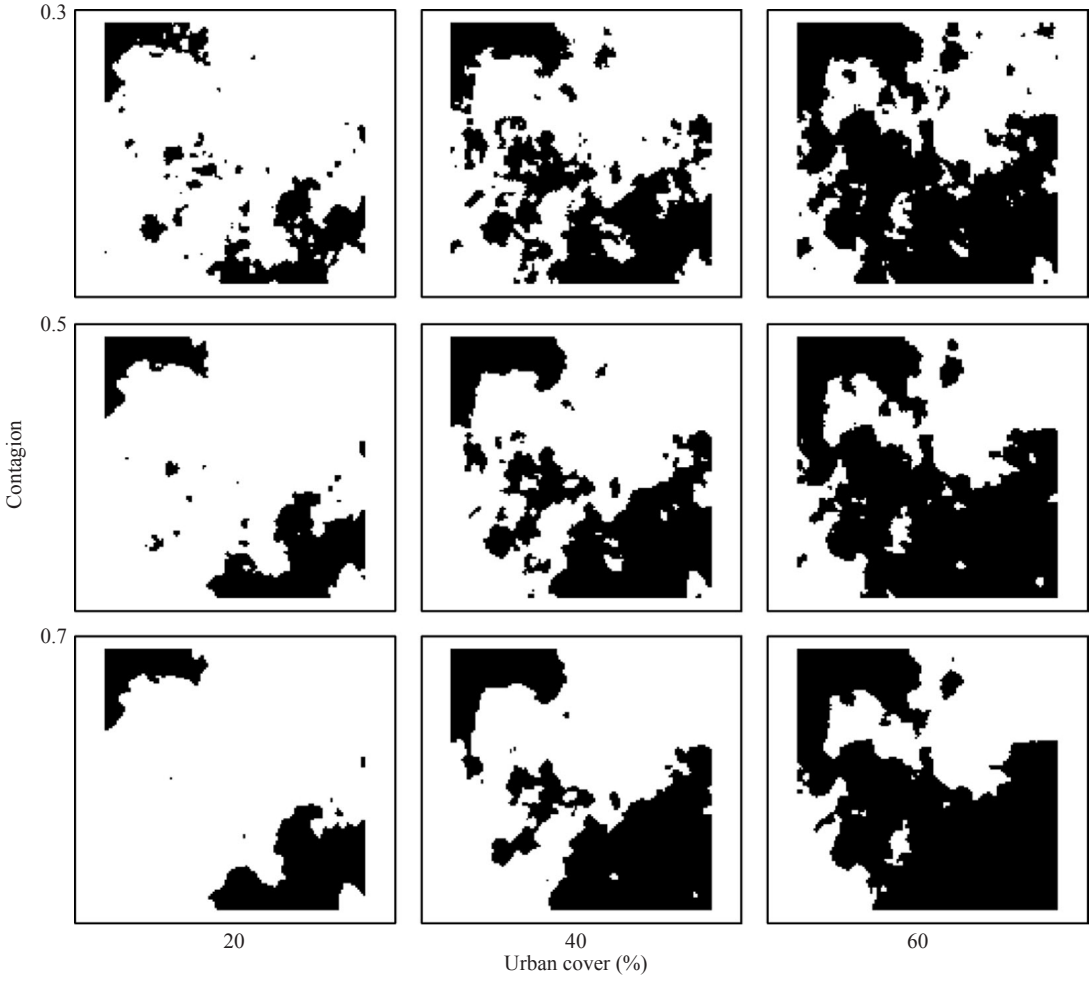


Figure 5. Artificial urban spatial patterns with varying contagion and percentage of urban cover.

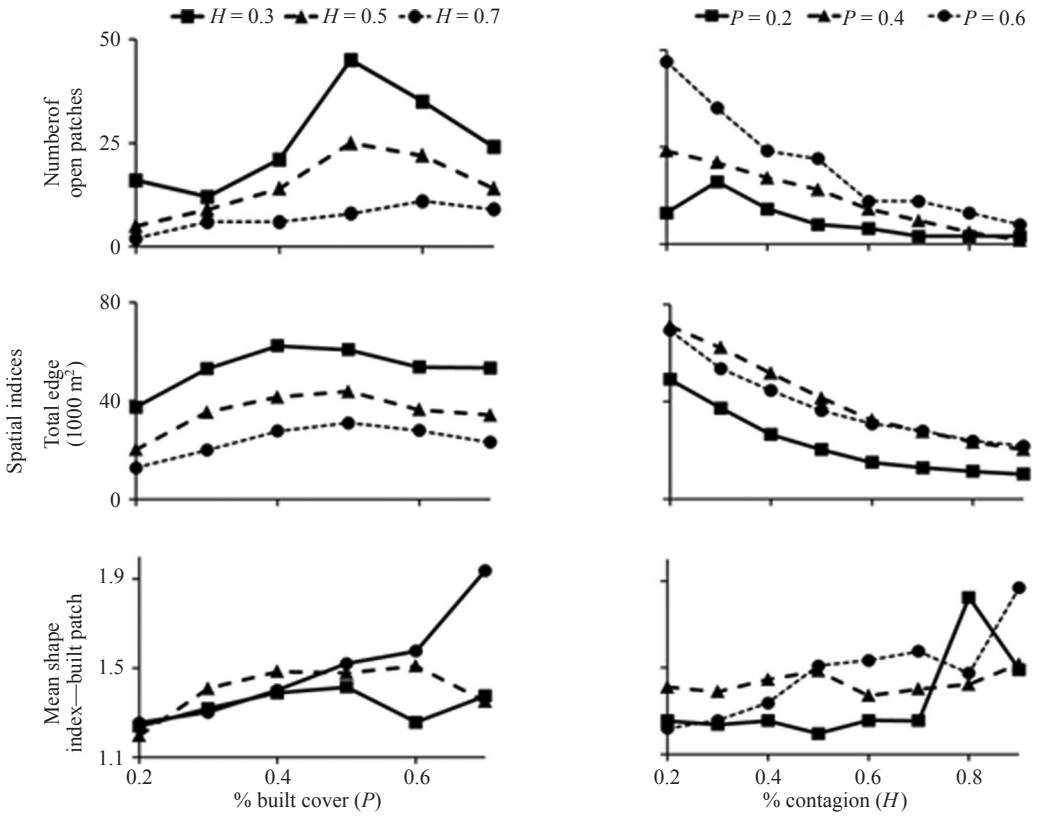


Figure 6. Sensitivity analysis of sprawl indices.

contagion and proportion of landscape cover that was built. Contagion is the degree of spatial aggregation of the built area, varying from 0 (no aggregation) to 1 (total aggregation).

We generated multifractal random maps (which, relative to the option of simple random maps, yielded patterns more similar to urban development) with low, medium, and high levels of contagion (varying from 0.2 to 0.9, in increments of 0.1) and low, medium, and high values of urban cover (varying from 20% to 70% urban cover, in increments of 10%). The protocol for generating the neutral landscapes using QRule is found in appendix B. A selection of the landscapes is displayed in figure 5. For each of these scenarios, we generated six landscape indicators (total number open patches, edge, mean shape index of built patches, total open core area, mean open core patch area, and connectivity).

Values for sprawl indices from the neutral landscapes are displayed in figure 6. In the left column, the *x*-axis represents increasing proportion of built space and its impact on six sprawl indices (*y*-axis), for three levels of contagion held at fixed values ($H = 0.3$, 0.5, and 0.7). In the right column, the *x*-axis represents incremental increases in contagion for three proportions of built space held at fixed values ($p = 0.2$, 0.4, and 0.6).

In several cases we see consistent trends in the response of sprawl indices to changes in percentage built cover and/or contagion. However, the trends are often dissimilar, so changes in the extent of built space, on the one hand, and changes in the configuration of built space on the other hand can have opposite impacts on sprawl index values. For example, the 'mean open core patch area' index is highest when built space is least and falls with increasing amount of built space. This index value is lowest at low levels of contagion (sprawl) and rises with increasing aggregation of built space (ie, compact development). Likewise, the 'total edge' index responds predictably to both extent and configuration of built space, but in different ways.

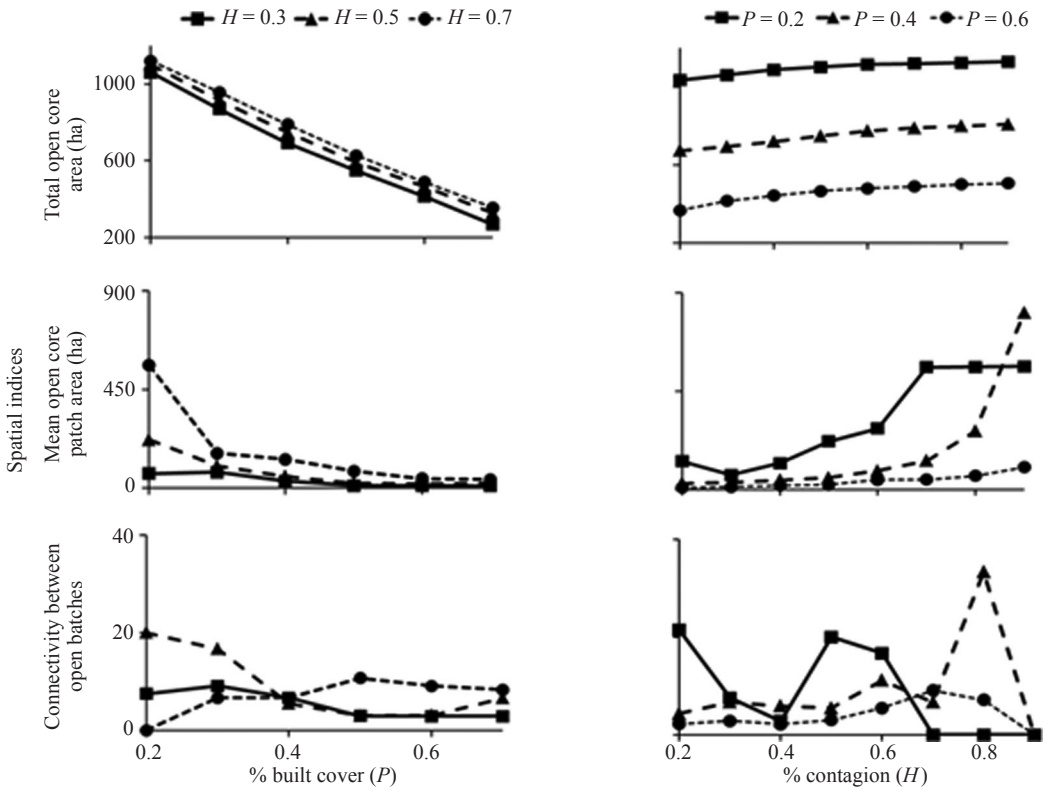


Figure 6 (continued).

For two indices in particular, mean shape index for built patches and connectivity of open patches, index sensitivity to changes in spatial extent and configuration of built space appears sporadic and unpredictable.

7 Discussion

Is sprawl occurring in Israel's Sharon subdistrict? This answer depends on how we address the aforementioned levels of complexity. We chose indices that would characterize spatial development of the region, and allow us to assess whether dispersed, leapfrog, strip or ribbon, and/or low-density development was occurring. Because sprawl is considered to be a relative phenomenon with regard to both time and space, we measured at two time periods and used two spatial scales of analysis to detect processes of change. According to most indices and both spatial scales, sprawl is observable throughout the region, though there are important exceptions.

The sprawl index, regardless of the method for quantifying built space, suggests that sprawl is occurring in regional councils and in the core city of Netanya, and is not occurring in the local councils. Results were more equivocal with regard to the region as a whole, and for Arab towns. Two methods suggest that Arab towns were becoming more compact, while DBScan suggests sprawl. The latter result seems to be due to an instance of isolated structures in a single town that were just within the threshold of being connected to a larger built space patch, producing a large, low-density patch.

According to indices that measure patch shape, amount, and distribution, sprawl seems to be occurring at both spatial scales. There are only two exceptions; DBScan suggests a decline in total edge for Netanya (likely due to the fact that infill is occurring), and a rise in patch connectance in the region. Declines in core open patch areas suggest loss of open spaces that would be viable for ecological preservation. The change in mean shape index of built patches

yields disparate results depending on the method and area of analysis. This observation, coupled with the inconsistent response of this index to variations in the neutral landscape, suggests that this particular index is unhelpful in spatial analyses of urban sprawl.

Landscape spatial indicators are not only sensitive to the level of aggregation, but also to the amount of built space. As shown in our use of neutral landscapes (figure 6), some variables (number of open space patches, total edge) reach their highest values at mid-range values of urban cover. Similar results were revealed by Gustafson and Parker (1992).

Several indices respond more predictably to changes in the neutral landscapes than others and are simpler to understand. These include number of open patches, total edge, and mean and total open core patch area. The responses of these indices are consistent across methods and all suggest that sprawl is occurring at the regional level. Total edge was only applied to the local-level analysis, where results are also consistent across methods (with the exception of Netanya). We conclude, then, that the claim that sprawl is increasing in our study region is robust and supported by the empirical data regardless of the method used.

However, the discrepancies that do exist suggest that conclusions can be crafted from the data presented depending on one's ideological predispositions towards the phenomenon called sprawl. Such ideological splits lie at the core of one of the prominent debates around the issue in the academic community. Planners Gordon and Richardson (1997; 2000) (exemplary of a community of scholars who do not consider sprawl to be undesirable) consistently argue in favor of minimal government intervention in markets and support for allowing individuals and markets the freedom to decide where and how to live. In contrast, planner Ewing (Ewing, 1997; Ewing et al, 2002) (as an example of scholars who consider sprawl as undesirable) links sprawl to a broad range of social, economic, and environmental problems. Both he and Gordon and Richardson criticize one another using qualitative and empirical evidence to refute the other's claims and to emphasize the desirable or undesirable aspects of sprawl. Yet at its core, much of their dispute is one of values: what is the ideal form of urban spatial development, how should society manage common property resources, and what is the proper role of government regarding intervention in societal affairs and markets? It is reasonable to assume that both sides bring data that support their positions, though much of the debate is normative.

Methodological differences also lie at the root of sprawl debates. Kline's critique (2000) of Nelson (1999), which provided support for the efficacy of growth-management policies in Florida and Oregon, focused on the data Nelson selected for analysis. When Kline employed alternative data, some supported Nelson's original conclusions, while some provided contradictory evidence. On the basis of Nelson's rejoinder (2000), the debate on data sources seems to have been concluded with some minor disagreements regarding data preference and the interpretation of results. Apparently, disputes regarding data sources are less contentious than ideological divides.

Exploring the implications of multiple data sources and sprawl measures further, we compared five studies which ranked sprawl in US metropolitan regions (Frenkel and Orenstein, 2011). We found some consistencies across analyses, but there were some results that were opposite between studies (that is, cities that were ranked the most sprawled in some studies were ranked the least sprawled in others, and vice versa). Here, too, differences in results were due to diverse methods of quantifying built space and choices of indices employed to define sprawl.

Each method (including the three used here) consists of an accumulation of small decisions that may ultimately have a profound effect on final estimates of built space (table 5). Since researchers should aspire to objectivity, we must recognize that small decisions may steer results towards certain conclusion.

Table 5. The importance of small decisions: sample methodological questions required to be addressed during the quantification of built space.

Method	Sample implementation questions	Decisions	Implications
Points	Data source	1:50 000 thematic maps	Low resolution; not all buildings represented.
	How to demarcate structures	Single data point	Must decide whether larger buildings (eg, warehouses, shopping malls) are assigned additional data points.
	How to transfer data point file into built space coverage	Use density of points to determine built space	Must choose specific point density that qualifies an area as built.
	How wide a radius with which to quantify building density?	30 m (convention established based on previous research using Landsat Satellite Data, which is 30 m resolution)	May automatically include additional area beyond the footprint of a building as built space or the opposite for large buildings.
DBScan	Data source	1:50 000 thematic maps	Low resolution; not all buildings present; dependent on temporal availability of maps.
	How to demarcate structures	Single data point	Must decide whether larger buildings (eg, warehouses, shopping malls) are assigned additional data points.
	How to convert data points into built space coverage	Use an automated algorithm that clusters points together based on their distances from one another; optimal distance is determined automatically	Open spaces between built structures are included or not in built space depending on configuration of structures and distances from one another. In present research, generally overestimates built space.
Polygons	Data source	High resolution orthophotos: digitization at 1:4000 scale	Highly accurate; dependent on temporal availability of orthophotos.
	How to demarcate structures	Delineation along the outer border of a community such that each community consists of one polygon	Open spaces embedded within built spaces defined as built. Built area estimate increased.
	How to deal with isolated built areas	Built areas of less than 10 000 m^2 excluded from definition of built space	Scattered, low-density structures ignored. Built area estimate reduced.

In order to move beyond potential disagreements, we offer four suggestions. First, the method for quantifying built space should be chosen according to what level of precision is important for the research question. The choice of methods and threshold decisions within each method will depend on the type of questions being examined [eg, ecological, hydrological, or urban planning (Clifton et al, 2008)]. Our points method defined built space narrowly, relative to the DBScan method, which also included lawns, urban parks, and small vacant lots within the rubric of built space.

Second, in interpreting empirical index values, context is crucial. In our data, sprawl index results suggest, for example, that local councils are becoming more compact, while the core city is becoming more sprawled. Familiarity with the demographic and residential development characteristics of each region is required in order to understand these trends. In general, local councils in Israel are urban settlements with fewer than 20 000 inhabitants. In the case of the local councils in the study region, they are primarily low-density residential suburbs that developed within former agrarian communities that are currently undergoing a certain degree of infill (a trend they may share with Arab towns, but for very different reasons). In these local councils, new homes are allotted a smaller amount of land per house than was allotted to homes in the original agricultural community. Regardless, the final density of these communities will likely be an order of magnitude lower than in the urban core region. Rural councils, although currently depopulating due to demographic and economic shifts, are beginning a process of residential development that, if current trends are an indicator, will lead to a greater resemblance to the local councils than their former agricultural communities. This means a higher density than previously, but also a density significantly lower than that of urban communities.

Third, some spatial indicators are more intuitive and predictable, and therefore, arguably more useful for analyzing spatial development patterns. In particular, mean open core patch size rises as contagion rises, while the number of open patches and the amount of edge fall as contagion rises. By contrast, connectivity yields no discernible pattern when tested on our artificially generated landscapes. Mean shape index and total open core area are largely insensitive to changes in contagion. We argue that three variables (number of open patches, total edge, and mean open core patch area) can thus be applied and explained most productively when discussing sprawl.

Finally, in regions where spatial changes are relatively robust, the general patterns of development should be discernable regardless of the method employed. In the study region the direction and pattern of spatial change were generally detectable over a series of methods and indices. The discrepancies provide the foundation for fine tuning the analysis and for further investigation as to the context of changes on the ground.

While these suggestions will not resolve the normative debate regarding the desirability of sprawl, they may help facilitate a discussion based on comparable data, a common terminology, and explicit research objectives.

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Appendix A. Equations for sprawl indices (McGarigal et al, 2002)

Equation 1

$$\text{Total edge} = \sum_{k=1}^{m} (e_{ik}) ,$$

where e_{ik} = total length of edge in landscape of given patch type i.

Equation 2

$$\text{Mean shape index} = \frac{1}{n_i} \sum_{j=1}^{n} (x_{ij}) ,$$

where n is the total number of a given patch type i, and x is the mean shape index for each given patch.

Patch shape index is defined as $p_{ij}/\min p_{ij}$, where p_{ij} is the perimeter of patch ij, and $\min p_{ij}$ is the minimum perimeter possible for a patch of the given number of rasters (ie, a perfect square).

Equation 3

$$\text{Total core area} = \sum_{j=1}^{n} a_{ij}^{c}\left(\frac{1}{10\,000}\right),$$

where a_{ij}^{c} is the core area of patch *ij* with an edge depth of 50 m, divided by 10 000 to convert to units of ha.

Equation 4

$$\text{Connectance index} = 100\left[\sum_{j=k}^{n} c_{ijk} \Big/ \frac{n_i(n_i-1)}{2}\right],$$

where c_{ijk} is the joining between patch *j* and *k* (0 = unjoined, 1 = joined) of the corresponding patch type *i*, based on a 100 m threshold distance, and n_i is the number of patches of the corresponding patch type.
Index values can range between 0 (no connection between patches in the same class) and 1 (all patches are connected).

Appendix B. Protocol for generating artificial urban patterns using Qrule

> Enter map type to be analyzed: Select <M> "Multifractal Random Map".
> Enter the number of levels and H (contagion):
    Select 7 levels (generating a 128 × 128 pixel grid)
    Select H varying from 0.2 to 0.9.
> Wrap map? No.
> Enter a negative random number seed: Enter a large, negative number (eg −88888).
> Enter the neighborhood rule Select 2 (N_nb = 8).
> Enter the number of map classes? Enter 1 (0 = "open" and 1 = "built").
> Enter the 2 probabilities, starting with p(0): Vary p(0), proportion of pixels "open", between 0.8 and 0.3. Vary p(1), proportion of pixels "built" between 0.2 and 0.7.
> Enter the number of replications? 100.
> Create an output map? Select "G" (generated map).
> Name of output file? Enter name of file.
> Perform map analysis? Select <N>, no analysis.
> What is the resolution of each grid element? Enter 30.