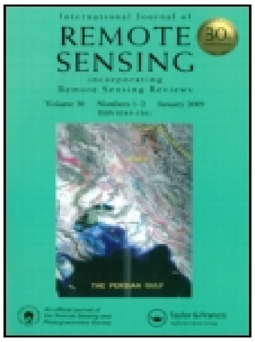

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How much is built? Quantifying and interpreting patterns of built space from different data sources

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Land-use/cover change (LUCC) has emerged as a crucial component of applied research in remote sensing. This work compares two methodologies, based on two data sources, for assessing amounts of land transformed from open to built space in three regions in Israel. We use a decision-tree methodology to define open and built space from remotely sensed (RS) Landsat data and a geographic information systems (GIS) platform for analysing 1:50 000 scale survey maps. The methodologies are developed independently, used to quantify and characterize the spatial pattern of built space, and then analysed for their strengths and weaknesses. We then develop a method for combining the built area maps derived from each methodology, capitalizing on the strengths of each. The RS methodology had higher omission errors for built space in areas with high vegetation levels and low-density exurban development, but high commission errors in the arid region. The GIS analysis generally had fewer errors, although systematically missed built surfaces that were not specifically buildings or roads, as well as structures intentionally omitted from the maps. We recommend using maps for baseline estimates whenever possible and then complementing the estimates with clusters of built areas identified with the RS methodology. The results of this comparative study are relevant to both researchers and practitioners who need to understand the strengths and weaknesses of mapping techniques they are using.

1. Introduction

1.1 *The importance of quantifying growth of built space*

Land-use/cover change (LUCC) is central to the most profound global and local environmental challenges facing humanity (Vitousek *et al.* 1997, Rindfuss *et al.* 2004,

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Lambin and Veldkamp 2005), including preservation of biodiversity (Velazquez *et al.* 2003, Defries *et al.* 2004), mitigation and adaptation to climate change (Feddema *et al.* 2005) and sustainable management of natural resources (Kummer and Turner 1994, Jiang *et al.* 2005). Among the most intense and permanent forms of LUCC is urbanization, defined in this work as the transformation of open land to built land (covered with a human structure, including buildings and roads).

Urbanization and the concurrent loss of open space is implicated in the decline of species richness in general (Ehrlich and Ehrlich 1981, Meffe and Carroll 1994), and in particular the loss of local species (Perry and Dmi'el 1995, Cam *et al.* 2000, Hennings and Edge 2003), habitat loss and fragmentation (Marzluff and Ewing 2001, McKinney 2002), and in the alteration of ecosystem function (Kemp and Spotila 1997). Within cities, higher human population densities have been found to correlate with areas of impoverished biodiversity (Turner *et al.* 2004) and the proliferation of built space may be linked to a decline in the value of ecosystem services at the watershed scale (Kreuter *et al.* 2001). Ecosystem services lost when land is transformed from open to built include carbon sequestration, air and water filtration, groundwater recharge and lost aesthetic and recreational use (Christensen *et al.* 1996, Costanza *et al.* 1997). Urbanization is inevitable and desirable to some degree, but without good information on patterns of change it is difficult to quantify and mitigate the effects and improve planning.

In Israel, rapid urbanization may be the country's foremost environmental challenge (Frankenberg 1999, Tal 2002). Rapid urbanization has characterized Israel's development since the country's inception in the middle of the 20th century, and suburbanization accompanied by increased motorization has characterized Israeli development over the past two decades of the 20th century (Shoshany and Goldshleger 2002, Tal 2002, Ayalon 2003, Frenkel 2004b). Israel is a relatively small country (22 000 km^2) with a disproportionately high amount of biological diversity due to its steep climate gradient, diverse topography and position as the only land-bridge linking three continents (Yom Tov and Mendelsohn 1988, Frankenberg 1999, Dolev and Perevolotsky 2004). Thus, knowledge of the rate and pattern of human development is essential to the establishment of policies that increase the probability of ensuring long-term ecological sustainability of the region's diverse ecosystems.

Since the early 1990s, Israel's planning authorities have prioritized the importance of protecting open land. This priority gained prominence during a period of massive immigration from the former Soviet Union, when there was significant pressure to convert large tracks of agricultural land to residential development (Alterman 2002). Concurrently, economic and demographic growth trends coupled with changing tastes in residential living encouraged out-migration from cities into suburban and exurban communities (Shoshany and Goldshleger 2002, Frenkel 2004a). Recognizing this process as deleterious, Israeli planners and policy makers adopted national development plans that emphasized the protection of open spaces. This process culminated in National Outline Plan 35, which explicitly aims to protect open spaces and limit inefficient (e.g. low density) land development (Shachar 1998, Golan 2005).

In this research, we estimate the amount and geographic distribution of open space transformation to built areas using two methodologies: one based on remote sensing, and one based on geographic information systems (GIS). Reliable estimates of built and open space are crucial for assessing the efficacy of open-space preservation policies. Our definition of open space is intentionally broad to include every land-cover type that qualifies as a non-built, non-paved surface (e.g. agriculture, sand dunes, forests, shrubland and other vegetation). Likewise, our definition of built land is broad, including any land covered by human infrastructure (e.g. buildings and roads). The distinction is drawn based on the ease with which land could be protected for the ecosystem services it provides or could provide. By limiting our investigation to two land-cover classes, we can focus more intensively on our objective of comparing results arising from the analysis of two different data sources.

1.2 *Quantifying built space: two approaches*

We derive independent estimates of built and open space from two distinct data sets: Landsat Thematic Mapper (TM) and survey maps. For each data source, we develop a separate methodology to generate quantitative estimates of built area for three study regions, conduct accuracy assessments for each and then compare the results of each methodology. We analyse the results for spatial and aggregate agreement and disagreement, and integrate the results into a final estimate of changes in the amount of built area. Through this process we can assess the strengths and weaknesses of each approach, analysing how the spatial characteristics of the built environment might be interpreted differently according to the methodology used to generate the data.

Integration of multiple data sources allows for better estimates of rates and types of land-cover change. Remotely sensed (RS) data obtained from satellite sensors have been the most popular starting point for information in this regard. Indeed, the growing understanding of the scale of LUCC is largely due to systematic monitoring of the Earth's surface using satellite data. Satellite data allow for monitoring of large areas of the Earth's surface at various scales of spatial resolution and at high temporal frequencies, and can thus be used to identify spatial and temporal change.

The Landsat TM sensor has been among the most popular resources for monitoring land cover (Cohen and Goward 2004) and has been used widely in assessing growth of built space (e.g. Ward *et al.* 2000, Yang and Lo 2002, Zhang *et al.* 2002, Yuan *et al.* 2005) and associated ecological impacts (Kreuter *et al.* 2001). The TM sensor and its Landsat predecessor, the Multispectral Scanner (MSS), provide a relatively long data record due to their length of continuous operation, their frequency of data capture over a given area, and a relatively high spatial resolution and a large area in each image. Furthermore, TM records reflectance data in seven spectral bands, including three in the visible spectrum and four infrared bands. The combination of visible and infrared wavelengths allows for distinction among land-cover types, including vegetation, soil and built space, through the use of semi-automated analyses over large geographic areas.

However, satellite data interpretation presents challenges (Rogan and Chen 2004). The source of remotely sensed data and the choice of methodology with which to interpret the data can influence the estimates of land-cover change; for example, the rates and extents of urbanization (Herold *et al.* 2003, Irwin and Bockstael 2008). It is often difficult, for example, to distinguish among land-cover types when relying exclusively on the seven TM bands (for reviews, see Cihlar (2000), Foody (2002)). Further challenges come in the form of mixed pixels, land surface variability and atmospheric interference of the satellite signal.

Accurately quantifying proliferation of built space in agricultural and semi-arid environments has proven particularly difficult. In heterogeneous environments like these, detecting urbanization is complicated by concurrent LUCCs, including differential vegetative response to rainfall patterns, spatially heterogeneous distribution of soil moisture, differential reflectance responses between fallow land and vigorously growing crops, and land manipulation in anticipation of development. Diverse and sometimes complex algorithms (Le Hegarat-Mascle *et al.* 2000, Duda and Canty 2002), spectral unmixing analyses (Elmore *et al.* 2000, Pu *et al.* 2008), decision trees (Martinez-Casasnovas 2000, Ward *et al.* 2000) and ancillary data sources (Le Hegarat-Mascle *et al.* 2000, Stefanov *et al.* 2001, Yang and Lo 2002) have been used to increase the accuracy of land-cover classifications. Digitized maps and GIS layers are commonly used to supplement initial TM-derived land-cover classifications in post-classification analyses.

As routine collection of satellite data only began in 1972, an analysis of longer-term LUCC requires use of older non-sensor-based survey maps (Petit and Lambin 2001, 2002). Maps, such as the 1:50 000 scale thematic survey maps used in this research, have been routinely produced through national surveys for almost a century. In many cases, maps are more accessible to researchers than are satellite data, and GIS methods of analysis of urbanization patterns are simpler and more intuitive to use. At the same time, reliance on survey maps has drawbacks in estimating LUCC. Maps are generalized and subjective representations of information surveyed or extracted from aerial photographs. In Mandate Palestine prior to 1948, British survey maps were produced through standard cartographic techniques, after which Israel used aerial photography to complement ground surveys (Gavish 1976). At low scales of resolution, cartographers may have to exclude information, for example when there may not be room for all the structures that exist in a given area (Weibel and Jones 1998, Petit and Lambin 2002). We compared the number of structures in randomly chosen sites within the 1:50 000 scale maps used in this research to those found in aerial photographs for the same areas and found that the maps graphically represented between one-half and one-quarter of the structures that appeared in the aerial photographs, with low-density areas being generally more accurate than high-density areas. Furthermore, maps often do not display actual land cover, but rather land use. In these cases, the physical characteristics of the land cover can only be assumed based on the land-use designation (e.g. agriculture, open space, sand dunes, or buildings).

Another limitation of using survey map data to examine LUCC is that they take time to produce and thus there is usually a delay between the specific point in time when the aerial photographs are captured, and when the map becomes available. In Israel, maps are generally ‘partially’ updated every 4 years (though more frequently for some areas of the country) and are published with a several-month lag. A further drawback is that the spatial extent of individual maps (e.g. 1:50 000 scale) is much smaller than, for example, a Landsat scene. This necessitates the collection of multiple maps to cover broad areas.

We set out here to produce built area maps using two data sources. In doing so, we aimed to (1) produce reliable estimates of the increase of built space between two periods, (2) assess the strengths and weaknesses of the methodologies used for interpreting each data source and (3) suggest a simple and intuitive way to combine data sets to increase the accuracy of the estimates, building on the strengths of each methodology and the predictability of the common built area types that may be overlooked by one methodology or the other. This methodological comparison, highlighting the strengths and weaknesses of the RS and GIS sources and analytical techniques, provides important information useful to both researchers and practitioners seeking to better understand patterns of urban growth.

2. Data and methods

2.1 *Study regions*

In this study, we analyse three geographically distinct regions in Israel: 130 km^2 of Mediterranean coast north of Tel Aviv ('Sharon', after the name of the geographic region), 140 km^2 of Mediterranean coast south of Tel Aviv ('Rishon', named after the city located at the centre of the study site), and 270 km^2 of northern semi-arid Negev Desert ('Beer Sheva', after the city at the southern edge of the site; figure 1). The study regions display both intra- and inter-region ecological, demographic and land-use heterogeneity. Communities in each region range from high-density cities to low-density rural communities within an agricultural matrix. These regions were chosen because: they are included within a single Landsat scene, path 174, row 38; they embody the conflict between farmland and/or open space preservation versus demands for increased housing and industrial development; and they form both a demographic (most of Israel's population is concentrated in the country's geographic centre) and an ecological gradient from Mediterranean ecosystems in the north to semi-arid desert in the south.

The Sharon study region is situated along the Mediterranean coast. The soils are primarily sandy-loam, with coastal sand dunes. The topography is generally flat, with elevations rising from sea level to approximately 80 m inland. Land use is dominated by irrigated agriculture and low- to medium-density rural and exurban communities (approximately 30% of land use). The 1983 population was 73 000 (560 persons/km^2), which rose to 110 000 (850 persons/km^2) by 1995.

The Rishon study region also lies in the Mediterranean coastal plain, approximately 20 km south of the Sharon region, and has similar topography and soils, with a higher predominance of bright sand dunes. Land use here is characterized by agriculture and high-density urban development. The western third of the study region consists of sand dunes and the southern edges of urban Tel-Aviv/Jaffa. The eastern portion of this region is dominated by rural communities and irrigated agriculture. Topography and soil types are similar to those of the previous region. The population of the area was 410 000 (2900 persons/km^2) in 1983 and 520 000 (3700 persons/km^2) in 1995.

The Beer Sheva study region lies in the northern Negev desert. The region includes one high-density urban community (Beer Sheva), several medium-density suburbs and towns, and dispersed rural settlements. The area is primarily open semi-arid shrubland, although much of the open space is used for rainfed grain production and some of the land has been forested with pine plantations and fruit trees, and some has been terraced and planted with dryland tree species at low densities ('savannazation'). Soils are loess and regosols, and the topography consists of moderately sloped foothills, wadis and plains with elevation ranging from 100 to 500 m above sea level. The population, predominantly in Beer Sheva, was 120 000 (440 persons/km^2) in 1983, rising to 180 000 (670 persons/km^2) in 1995.

2.2 *Definition of built space*

The primary objective of the data analysis was to assess changes in the area and geographic distribution of built space between two points in time. We define built space as land covered with a physical, anthropogenic structure: primarily buildings and roads. However, the interpretation of built space required different

Figure 1. Study regions.

methodologies for each of the two data sources. Analysis using the satellite data assumes that built space has a spectral signature distinct from other land-cover types. This definition is synonymous to impervious surfaces. In the survey map data, built space is defined as land covered by either a building or a road or in close proximity to a building or road (see below), and open space is the inverse (not covered by or in close proximity to a building or road). Built space using the GIS definition is not necessarily impervious surface (e.g. low-density development).

2.3 *Landsat TM analysis: built land cover classification using remote sensing*

To generate remote sensing-derived estimates of change in built land, we compared the 8 April 1987 Landsat TM scene for WRS Path 174 Row 38 with that of 6 April 1998. Data from the early spring capture the height of annual plant productivity, minimizing the amount of unvegetated agricultural areas and thus making it easier to distinguish between built land and open soil, which have similar spectral signatures (figure 2).

The proximity of the date of acquisition of two images reduced the likelihood of phenological differences between the two scenes, thus minimizing misidentification of changes due to natural seasonal variations. Rainfall during the preceding 7 months was 812 mm in 1987 (150% above the long-term average) and 548 mm in 1998 (similar to the long-term average; data from the Nir Galim meteorological station, approximately 20 km south of the Rishon region). During both seasons, rain fell primarily in November and December. We would not expect large differences in vegetated cover between these two dates in the Mediterranean sites because vegetation in this climate zone is not sensitive to precipitation differences of the magnitude observed (Kutiel *et al.* 1995). However, small differences in precipitation in the semi-arid region do affect plant productivity (Kutiel *et al.* 1995, 2000), and will increase classification errors.

The TM images were co-registered to within one pixel (30 m) accuracy and georeferenced by aligning the imagery to a vector file of major roads. Both images were converted to reflectance using the Landsat calibration coefficients and a dark pixel subtraction method to account for differences in atmospheric scatter (Chavez 1988). Finally, the spectral bands of the 1987 scene were aligned to those in the 1998 scene using gain and offset values derived from a comparison of reflectance values between the two scenes in areas of unchanging land cover (Schott *et al.* 1988, Elmore *et al.* 2000). This spectral alignment allowed us to identify open space using the same

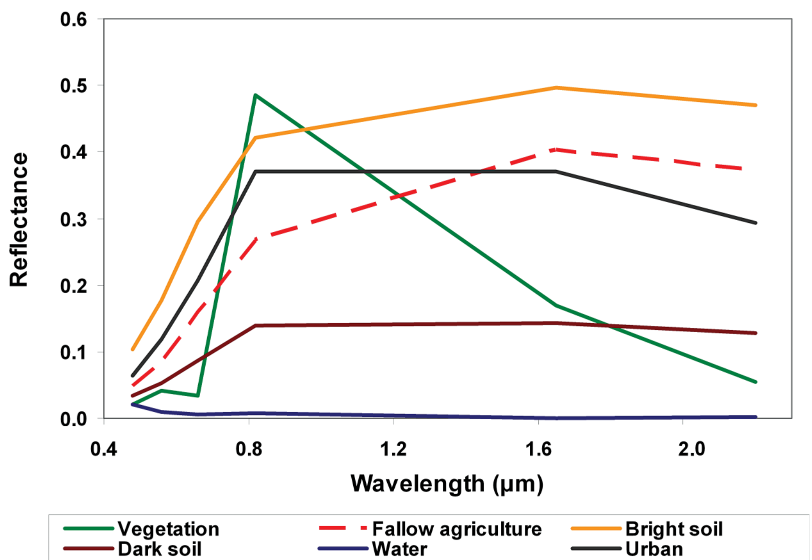

Figure 2. Landsat spectra of land-cover classes.

Table 1. Threshold values used to classify non-built land cover.

	Sharon	Rishon	Beer Sheva
Vegetation	NDVI > 0.5	NDVI > 0.5	NDVI > 0.4
Fallow Agriculture	B_7/B_1 ratio > 4.5	B_7/B_1 ratio > 4.5	B_7/B_1 ratio > 4.5
Bright Soil	$B_7 > 0.3$	$B_7 > 0.35$	$B_7 > 0.3$
Dark Soil	$B_1 < 0.05$	$B_1 < 0.05$	$B_1 < 0.05$
Water	$B_5 < 0.1$	$B_5 < 0.1$	$B_5 < 0.1$

NDVI, Normalized difference vegetation index $= (B_4 - B_3)/(B_4 + B_3)$.
B_1, B_3, B_4, B_5 and B_7 represent reflectance values for Landsat TM spectral bands 1, 3, 4, 5 and 7, respectively.

methodology for both time periods. Both images were clipped to encompass only the Sharon, Rishon and Beer Sheva study regions, corresponding to the GIS survey maps.

To identify built areas at both points in time, we used a decision-tree approach to classify non-built land-cover types. We defined open space based on reflectance spectra of training pixels known to contain dense vegetation, fallow agriculture, bright soil, dark soil and open water. Classification thresholds were selected based on values that excluded 100% of training pixels known to contain urban/built space (table 1). Thresholds were deliberately selected to correctly classify all urban pixels, even if some non-urban pixels were misclassified in order to encompass the spectral heterogeneity of the built landscape. Selected thresholds also classified 100% of open space training pixels with the exception of fallow agriculture. The band 7/band 1 ratio included 100% of urban training pixels, but excluded only 60–65% of fallow agriculture depending on the study region. The average spectral signatures of the training pixels are shown in figure 2. While we kept the mask threshold values as consistent as possible among the three scenes, we used a lower vegetation threshold in Beer Sheva because of the prevalence of low-density vegetation and a higher bright soil threshold in Rishon because built areas are often developed on sand dunes. This approach reduced the number of non-built areas identified as built (e.g. reduced commission errors), but also reduced the number of built areas correctly identified in the two regions (e.g. increased omission errors).

The remaining land cover that was not masked included built areas as well as areas containing mixed vegetation and soil (e.g. urban vegetation, mixed fallow agriculture, vegetated sand dunes in Rishon and semi-arid shrubland in Beer Sheva). To differentiate between built areas and low-density vegetation we used spectral unmixing (Adams *et al.* 1995), a mathematical process that defined the reflectance values of the remaining pixels as linear combinations of image endmembers from built and vegetated land cover. Single image endmembers were selected from a city centre (built) and a cultivated agricultural plot (vegetated). Endmembers were selected from a sampling of 20–30 built and vegetated pixels across the three study areas. Image endmembers approximated the mean reflectance spectra of the sample pixels, and were the same spectra used in the initial decision-tree classification (figure 2). A reflectance threshold value of 50% built cover as defined by spectral unmixing were retained as built, while pixels containing less than 50% built cover (assumed to be semi-arid vegetation) were masked. A 50% threshold was used to define each pixel based on whether the majority of pixels were built or open. The resulting image for each time period comprised open (non-built) or built pixels. Built land cover in 1987 was subtracted from built land cover in 1998 to produce a change map identifying areas of expansion of built space between the two time periods.

To further address the difficulty in identifying open pixels with spectral signatures similar to built cover, we applied a smoothing filter (Yang and Lo 2002) using a 3×3 pixel moving window to reclassify pixels according to the majority pixel value within the window. This removed stray change pixels associated with spectrally similar semi-arid land cover as well as those associated with scene offsets along roads.

2.4 *GIS map analysis: defining open and built land and quantifying the transition between land-cover classes*

Survey maps, at 1:50 000 scale, produced by the Survey of Israel (collected from the cartography library of Hebrew University) were scanned and digitized. The maps analysed were those closest in date to the Landsat TM data (1987 and 1998). For the Sharon area, maps were from 1989 and 1999, for Rishon they were from 1985 and 1999, and for Beer Sheva, from 1984 and 1999.

Built structures on the maps were digitized as points, and paved roads were digitized as lines. Digitized maps from the 1980s were used as a baseline, and new structures were added based on the 1990s maps. Single points rather than polygons were used to describe structures to reduce the time required to digitize the survey maps, and because structure density was easier to measure with point data.

The built vector files for each location and time period were converted into structure density raster grids with 30 m resolution using a 30 m search radius and a kernel density function, which weights the centre of the search radius more heavily than the edges, producing a smoother density distribution. A 30 m resolution was chosen to correspond with TM spatial resolution, and because a 30 m radius was wide enough to ensure that the spatial footprint of large buildings would be included as built. A pixel was defined as built if it contained at least one structure or was within 30 m of a structure (thus with a pixel threshold value of ≥ 1) was defined as 'built'. The road files were converted into raster grids using the same methods. Note that because of the binary open-built definition, most pixels are likely to be a fraction of each cover type (see section 3.1). The road and structure layers were aggregated for each of the two time periods to create a raster grid of 'built' area.

2.5 *Combining RS/GIS maps for comparison*

To compare the results from both the RS and GIS analyses, we created raster maps of either no change (remain open or built) or change (open to built) for both methodologies. We assumed that no transitions from built to open occurred during this time period because of the high development rates in these parts of Israel. The two maps were combined to identify four distinct classes: (1) open space according to both methods; (2) built space according to RS only; (3) built space according to GIS only and (4) built space according to both methods. The result was a single change map for each study region that displayed the amount and spatial configuration of agreement and disagreement between the RS and GIS methodologies in assessing land-cover change between open and built.

Our final task was to create a built area map that exploited the advantages of both methodologies to maximize accuracy of our final estimates. Our aim was to use the most accurate map (in our case, the GIS-derived map) as a base map, and add supplementary information regarding built spaces from the auxiliary map (here, the

RS-derived map). After comparing the RS and GIS results quantitatively, we analysed the qualitative land-cover types that were defined as built by the RS methodology but not by the GIS methodology.

2.6 Accuracy assessment

We separately conducted an accuracy assessment of the individual and combined methodologies using a 2001 orthophoto to check the accuracy of approximately 750 randomly selected pixels for each study region in the 1990s RS and GIS maps. These pixels provided us with an estimate of the proportion of built to open space (true cover) and were also used to assess the accuracy of our maps. Although a stratified sampling may have been preferred to increase precision over the simple random sampling and to ensure adequate representation of the rarer land cover class (Stehman and Czaplewski 1998), we chose random sampling because we had a large enough sample size to ensure adequate representation of the rarer class (Foody 2002). For example, in Beer Sheva, where built area was the rarest of the three study sites, over 100 points fell in built areas. Our large sample size also suggested that precision gains through stratified sampling would have been minimal. Had we been working with more land-cover classes, including rarer types, a stratified sampling technique may have been more appropriate.

When determining land-cover class in the orthophoto, we considered both the dominant land cover within each pixel and the dominant land cover in a nine-pixel matrix with the selected pixel at the centre (Stehman and Czaplewski 1998). This latter step helped us to differentiate between registration errors and errors arising for other reasons. For both methodologies we investigated the nature of omission and commission errors for each of the pixels that were erroneously defined as either built or open in order to reveal underlying patterns in the errors observed. Overall accuracy is defined as the total probability that a pixel was classified correctly (Stehman and Czaplewski 1998) and is the sum of the correctly classified pixels in each category divided by the size of the sample.

We did not conduct an accuracy assessment for the 1980s map because the only spatial data we could access were the survey maps and the satellite imagery, which were both used in the research. Orthophotos were not available for this time period, and aerial photographs were not suitable for accuracy assessment because they were used to produce the survey maps and thus would introduce a favourable bias towards the GIS maps.

3. Results

3.1 Accuracy assessment

The error matrices and overall accuracy of the maps produced by the two methods are shown in table 2. For the RS method, the overall accuracy was approximately 85% for each of the study regions. For the GIS method, the overall accuracy was 87, 79 and 92% for the Sharon, Rishon and Beer Sheva regions, respectively. While the overall accuracy of both methods was about 85%, the source of errors differed greatly.

For the RS methodology, commission errors (false positives, or the proportion of all land defined as built that was, in reality, open) were highest in the Beer Sheva region, with 52% commission errors as compared to 21% and 8% in Sharon and Rishon, respectively. A majority (56%) of the commission errors in the Beer Sheva

Table 2. Accuracy assessment results for the 1990s for (*a*) Sharon, (*b*) Rishon and (*c*) and Beer Sheva built area maps derived from the (*i*) RS and (*ii*) GIS analyses, including error matrices, commission and omission errors, overall accuracy and Kappa index. Slight inconsistencies are due to rounding errors.

Study area		Orthophoto reference: Open	Built	Mapped coverage
(*a*) Sharon				
(*i*) RS map	Open	0.73	0.13	0.86
	Built	0.03	0.11	0.14
	True coverage	0.76	0.24	1.00
Commission error: 0.03/0.14 = 0.21; Omission error: 0.13/0.24 = 0.54				
Overall accuracy: 0.73 + 0.11 = 0.84; Kappa index = 0.48				
(*ii*) GIS map	Open	0.70	0.07	0.78
	Built	0.05	0.17	0.22
	True coverage	0.76	0.24	1.00
Commission error: 0.05/0.22 = 0.23; Omission error: 0.07/0.24 = 0.29				
Overall accuracy: 0.70 + 0.17 = 0.87; Kappa index = 0.64				
(*b*) Rishon				
(*i*) RS map	Open	0.52	0.12	0.64
	Built	0.03	0.33	0.36
	True coverage	0.55	0.45	1.00
Commission error: 0.03/0.36 = 0.08; Omission error: 0.12/0.45 = 0.27				
Overall accuracy: 0.52 + 0.33 = 0.85; Kappa index = 0.69				
(*ii*) GIS map	Open	0.49	0.15	0.64
	Built	0.06	0.30	0.36
	True coverage	0.55	0.45	1.00
Commission error: 0.06/0.36 = 0.17; Omission error: 0.15/0.45 = 0.33				
Overall accuracy: 0.49 + 0.30 = 0.79; Kappa index = 0.56				
(*c*) Beer Sheva				
(*i*) RS map	Open	0.75	0.04	0.79
	Built	0.11	0.11	0.21
	True coverage	0.85	0.15	1.00
Commission error: 0.11/0.21 = 0.52; Omission error: 0.04/0.15 = 0.27				
Overall accuracy: 0.75 + 0.11 = 0.85; Kappa index = 0.50				
(*ii*) GIS map	Open	0.83	0.06	0.89
	Built	0.03	0.09	0.11
	True coverage	0.85	0.15	1.00
Commission error: 0.03/0.11 = 0.27; Omission error: 0.06/0.15 = 0.40				
Overall accuracy: 0.83 + 0.09 = 0.92; Kappa index = 0.62				

region occurred on semi-arid pixels with similar spectral signatures to built pixels (figure 3). These areas included terraced hillsides, dry river beds, hill slopes with patchy shrub vegetation and outcroppings of bedrock. The remaining RS commission errors were primarily due to registration errors.

At 55%, the Sharon region had the highest number of RS omission errors (land that was built, but which was erroneously defined as open), with Rishon and Beer Sheva at 26% and 27%, respectively. In all three regions, these errors occurred primarily in suburban built areas with high vegetation cover. This type of development was most prevalent at the Sharon region. Additional omission errors in the three regions were caused by registration errors and new construction that occurred between the time the satellite data were captured and the date of the orthophoto (D. Orenstein, personal observation).

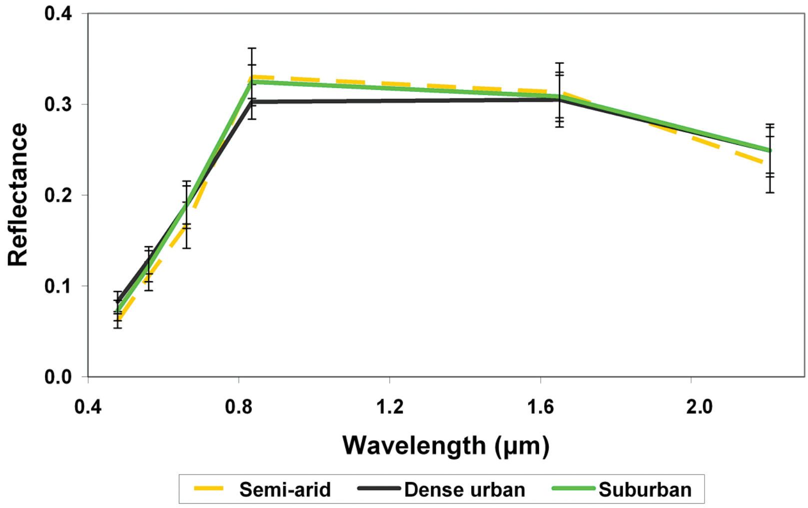

Figure 3. Spectral signatures for semi-arid soils, dense urban and suburban settlements in the Beer Sheva region.

GIS commission errors ranged between 17% (Rishon) and 27% (Beer Sheva), while omission errors ranged between 29% (Sharon) and 40% (Beer Sheva). Commission errors in the GIS method were due to registration errors, errors in the data included in the map, or user errors in the process of digitization. The latter two sources of errors, which apply to both commission and omission errors, require further explanation. With regard to map-based errors, because of the scale of the map (1:50 000), not every structure could be recorded, in particular for highly dense areas. This led to an under-representation of built area, particularly within the urban matrix. Furthermore, designating each building with a single, one-dimensional data point (or even two or three points) did not always suffice to capture the footprint of some of the largest buildings (e.g. factories and warehouses).

Omission errors in the GIS methodology resulted from a broader array of causes. These include the map and user errors described in the previous paragraph, infrastructures that qualify as built but do not appear as such on the map, and built area that was intentionally removed from the map due to security concerns.

Many areas that are effectively paved or built cannot be identified as such from the maps. Areas like this include cemeteries (which in Israel are very densely covered with stone and not vegetated), landfills and areas with high amounts of construction waste, sewage treatment facilities and parking lots (table 3).

Military bases had been censored from the maps and the orthophotos. These built areas were identified with the RS methodology, and their presence confirmed by *a priori* knowledge and Google Earth®. Approximately 14% of the omission errors in the Rishon area were built areas intentionally removed from the maps.

In the aggregate, registration errors caused roughly equal numbers of omission and commission errors. This is also true of errors arising from faulty placement of digitized points. Although these errors reduce accuracy, they do not affect the net estimate of the built area. The relative values of the Kappa indices confirm the trends we had noted using the other accuracy indicators.

Table 3. Strengths and weaknesses of using either GIS or RS methods and data sources for defining built area.

GIS map-based approach	RS satellite data-based approach
Correctly identifies:	Correctly identifies:
• High-density development	• High-density development
• Rural and low-density development	• Large structures (factories, warehouses) that cover more land surface than the single data point in the GIS study would account for
• Roads	• Impervious surfaces such as parking lots, cemeteries
• Small stand-alone structures	
Misidentifies:	Misidentifies:
• Impervious surfaces such as parking lots, cemeteries	• Rural and low-density development including narrow or unpaved roads
• Large structures (factories, warehouses) that cover more land surface than the single data point in the GIS study would account for	• Open space with similar spectral properties to built areas (e.g. sand dunes, semi-arid scrubland)
• Structures intentionally or unintentionally omitted from maps	

3.2 *RS classification*

The decision-tree classifications of non-built land cover successfully identified a majority of open space in each time period and study area. However, the additional spectral mixture analysis was necessary to further refine the classification of built pixels (table 4). This was particularly true in the semi-arid Beer Sheva site. For example, in 1987 the decision tree alone classified 96 901, or 25% of pixels in Beer Sheva as built. The addition of the spectral mixture analysis reclassified the number of built pixels to 16 279, or 4% of pixels.

Table 4. Number of pixels in the (*a*) Sharon, (*b*) Rishon and (*c*) Beer Sheva study regions defined as open and built by RS using a decision tree alone, and a decision tree plus spectral mixture analysis (SMA).

	1987		1998	
	Decision tree	Decision tree + SMA	Decision tree	Decision tree + SMA
(*a*) Sharon				
Classified as open	187 662	188 172	174 162	178 036
Classified as built	7129	6919	20 929	17 055
(*b*) Rishon				
Classified as open	119 723	155 750	131 528	142 928
Classified as built	75 478	39 451	63 673	52 273
(*c*) Beer Sheva				
Classified as open	296 030	376 656	243 215	321 027
Classified as built	96 901	16 275	149 716	71 904

3.3 *Comparison of RS/GIS built estimates*

According to the GIS analysis, there were 29, 20 and 71% increases in built land in the Sharon, Rishon and Beer Sheva regions, respectively (figure 4). The RS analysis showed 200, 42 and 280% increases, respectively. Even the lower estimates of the GIS analysis suggest a profound and rapid increase in built area.

The RS estimates of built area for the Sharon region were lower at both points in time than those generated by the GIS analysis, although the gap closes slightly in the 1990s. For the Rishon region, estimates were much closer between the two methods for the 1980s, and similarly to the Sharon region, the gap closes by the late 1990s. For the Beer Sheva region, the RS estimate of built area was similar to that of the GIS estimate in the 1980s, but the RS estimate of built area increased nearly fourfold in the 1990s, surpassing the GIS estimate for total developed area in the 1990s, which had also increased by 71%.

RS estimates of developed area were lower than the GIS-derived estimates in five of six cases. The largest differences were for the Sharon region in the mid-1980s, where the RS estimate is less than one-quarter of the GIS estimate, and for the Beer Sheva region in the mid-1990s, where the RS estimate is 58% higher than the GIS estimate.

In the 1990s, five out of six estimates of built area underestimated the amount of built land when compared to the high-resolution orthophoto (figure 4). This is consistent with the results of the accuracy assessment, which revealed consistently larger omission errors than commission errors for built area estimates. The exception is the RS-derived map of built area for the Beer Sheva site, where commission errors were high (see section 3.4). The actual proportion of built space in the 1999, according to the orthophoto-sampling, was 24, 45 and 15% in Sharon, Rishon and Beer Sheva, respectively.

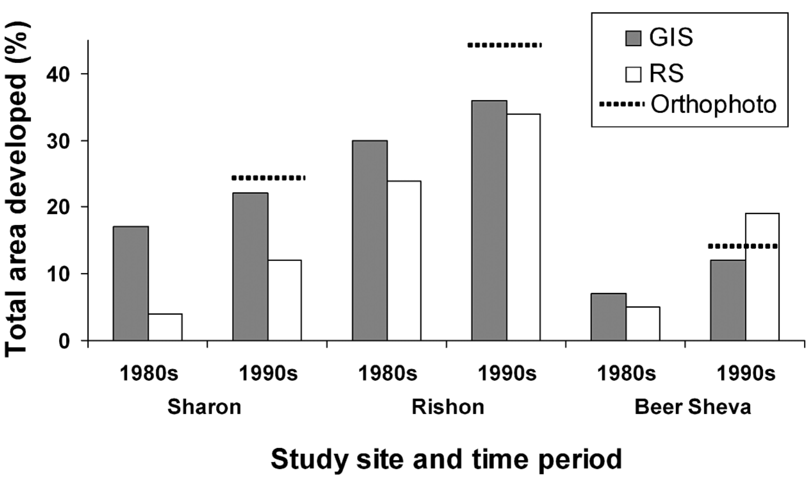

Figure 4. Estimates of built area using GIS and RS methodologies for two time periods, P1 (1980s) and P2 (1990s), in three research regions. For the 1990s, the results are compared to true cover based on a 750-pixel sampling from high-resolution orthophotos.

3.4 *Spatial agreement/disagreement between the RS and GIS methodologies*

A visual comparison of the results of the GIS and RS analyses (figures 5–7) shows that clusters of densely built area are detected similarly by both methods. However, fine-scale differences in the spatial patterns of built space are also visible. The RS assessments of built area contain considerable noise, in particular in the western portion of the Rishon region (figure 6), which corresponds to the presence of sand dunes, and in the centre of the Beer Sheva region (figure 7), corresponding to semi-vegetated hills. In the RS analysis, only the largest roads were defined as built. Smaller roads are too narrow to be defined as built by the RS methodology.

For the Sharon region during the 1980s, the GIS method identified far more area as built than the RS method (2300 ha as compared to 580 ha). Spatial agreement on built area is primarily found in the major cities. Most of the area detected as built by the GIS methodology, but not the RS methodology, is found in rural, low-density communities or roads (figure 5(*a*)). The pixels that were defined as built by the RS method but not the GIS method, equivalent to 240 ha, were in the higher-density communities of Tira and Netanya (lower-right and upper-left corners of the map, respectively, in figure 5(*b*)), along the sandy coastline (e.g. misidentified as built due to similarities in spectral signatures or minor registration errors) and along roads.

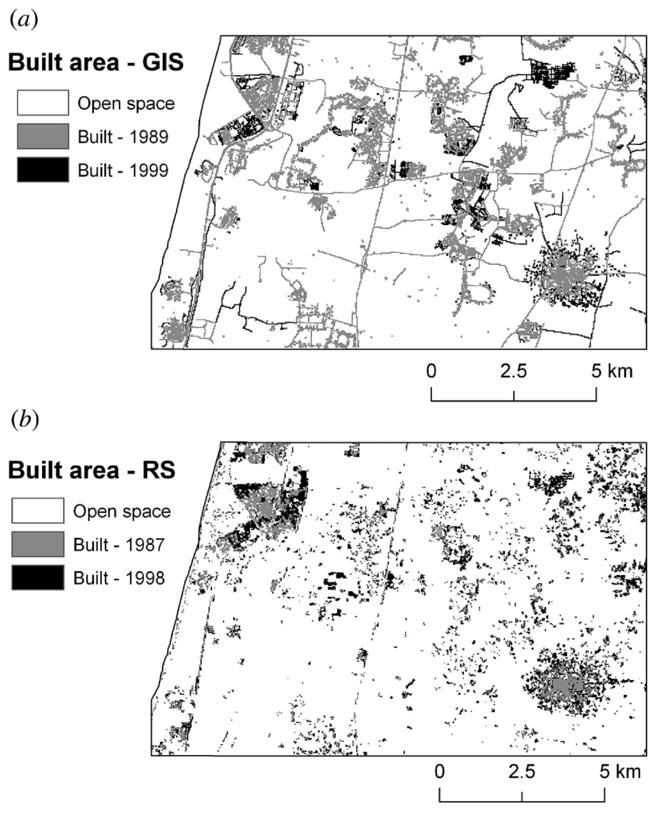

Figure 5. Built area for the 1980s and 1990s in the Sharon study region as measured by (*a*) GIS and (*b*) RS analysis.

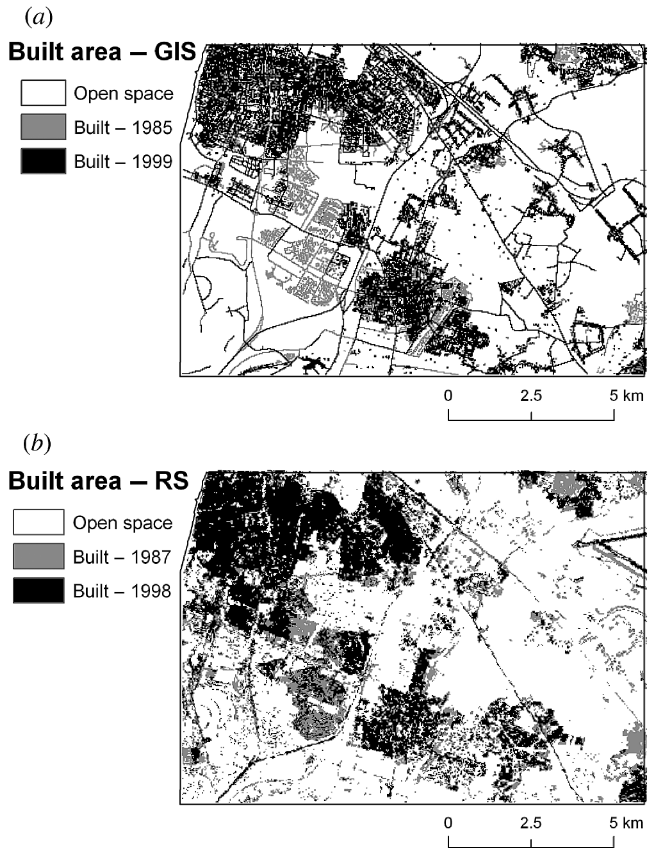

Figure 6. Built area for the 1980s and 1990s in the Rishon study region as measured by (*a*) GIS and (*b*) RS analysis.

Similar relationships are found in the Sharon 1990s analysis. However, the difference in total built area between the two methods is smaller. We attribute this to intensive development in the region that occurred during the interim period, including intensification of development in rural areas. As noted, a major fraction of the built areas detected with the GIS method but not with the RS method consisted of low-density rural areas. In the Sharon, the development of low-density rural areas into higher-density built areas was common during the study period, thus these areas became detectable by the RS methodology.

The spatial disagreement between pixels defined as built by only one of the two methods is more pronounced in the Rishon region (figure 6). For the analysis in the 1980s, 4200 ha of land were defined as built only by the GIS methodology, while 3200 ha were defined as built by RS only. The GIS methodology detected roads and rural development and a few pixels in urban areas that RS did not detect. The unique pixels detected by RS were primarily in urban areas, but also some sand dunes (i.e. misidentified) and developed areas not found on the maps (including the airport runway, a cemetery and military installations). These patterns were repeated in the Rishon analysis in the 1990s. The Rishon area is characterized by significantly higher density development than the Sharon region. Accordingly, we see a far greater

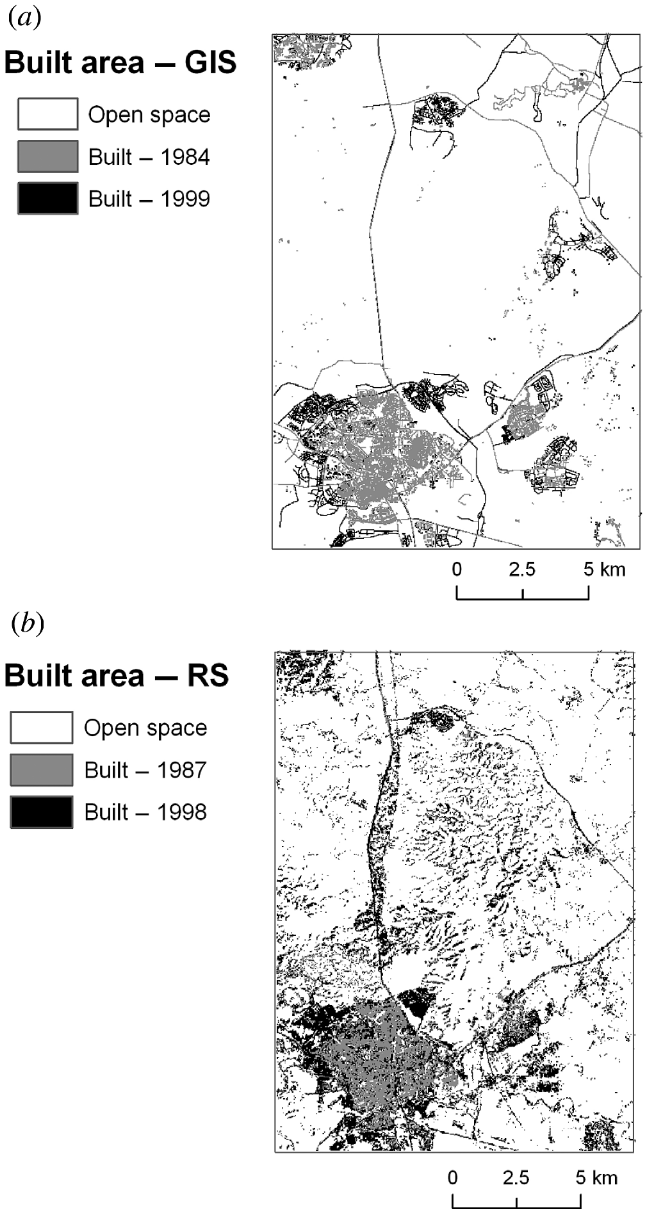

Figure 7. Built area for the 1980s and 1990s in the Beer Sheva study region as measured by (*a*) GIS and (*b*) RS analysis.

proportion of the area defined as built during both periods (15–20%) in Rishon than in the other study regions.

The patterns of built area produced by the two methodologies for the southern, semi-arid Beer Sheva region differ significantly (figure 7). For the 1980s analysis, 1100 ha of land were defined as built by only the GIS method, while 580 ha were defined as built only by the RS method. Undetected by the RS analysis were low-density settlements and roads, as well as scattered pixels within urban centres. Approximately two-thirds of the land defined as built by the RS methodology, but open by GIS, were also in dense urban areas or along roads, while the rest was found in open shrubland areas or in built areas excluded from the maps. For the 1990s analysis, there is more land defined as built exclusively by the RS method than defined as such exclusively by the GIS method. Again, built areas defined as such only by the GIS method were split between rural settlements and roads, and by built land in urban areas. As observed in the accuracy assessment, approximately one-third of the land defined as built only by the RS method was in shrubland areas or areas used for low-density tree planting. These were misidentified as built due to their spectral signature similarities to urban areas. The remaining RS-only built pixels were in urban areas and approximately 10% in built areas intentionally or unintentionally excluded from the maps.

3.5 *Constructing a best-estimate built area map*

We defined three main types of built area that were misclassified in the GIS base map but correctly identified in the RS auxiliary map: (1) infill in urban residential and industrial areas, (2) built areas that had been purposely or inadvertently excluded from the maps, including newly built areas and (3) infrastructures that are not structures *per se*, but are paved surfaces (including sewage treatment plants, waste disposal facilities and agricultural installations). These land-cover types were added to the GIS map from a filtered RS built map for the Rishon site (figure 8). The estimate of total built area for the GIS + RS map rose from 5100 to 6600 ha, omission errors were reduced from 34 to 9%, while commission errors were statistically unchanged. The overall accuracy of the final map was 87%, as compared to 78% for the original GIS estimate, and the Kappa index is accordingly larger. The combined map is shown in figure 8(*c*), and table 5 displays the confusion matrix for the improved map.

Combining the GIS and RS maps was less effective for the semi-arid Beer Sheva region, which was characterized by large blocs of open soil misidentified as built space in the RS analysis. The filtering was less effective at removing the pixels responsible for commission errors, so the combined map had 49% commission errors (nearly twice the number as the GIS map alone), although omission errors were significantly reduced (to 12%) relative to the original GIS map. Overall accuracy was 86%, which was lower than the accuracy of the GIS map alone.

Our best estimates of increases in total built area in the three research regions between the mid-1980s and the mid-1990s are: 15–22% in the Sharon region, 35–45% in the Rishon region and 8–20% in the Beer Sheva region. Supplementing the GIS estimates with RS estimates of built area resulted in an upward adjustment of between 1 and 15% of built land, depending on the region. The addition of RS data had the least effect in the rural area of Sharon, and the greatest in the densely built Rishon region.

4. Discussion

Much of the recent literature on methodological approaches to land-cover classification treat GIS maps as a secondary, or ancillary, data set with an RS product as the primary source (Vogelmann *et al.* 1998, Yang and Lo 2002). While both approaches have unique strengths and weaknesses, we argue that a GIS-based analysis of built areas yields more predictable errors that can be largely resolved with the addition of a

Figure 8. Map of built pixels as defined by (*a*) GIS analysis, (*b*) RS data that had not been defined by GIS and (*c*) final built area estimate, defined by GIS, with addition of supplementary RS data, for Rishon, 1998/99: (*i*) a sewage treatment facility; (*ii*) a new development that occurred after publication of the map and (*iii*) a developed area intentionally excluded from the map.

Table 5. Results of the accuracy assessment for the GIS–RS combined ('best estimate') built area map for Rishon (1990s), including error matrices, commission and omission errors, overall accuracy and Kappa index. Slight inconsistencies are due to rounding errors.

	Orthophoto reference		
	Open	Built	RS mapped coverage
Open	0.47	0.04	0.51
Built	0.09	0.40	0.49
True coverage	0.55	0.45	1.00
Commission error: 0.09/0.49 = 0.18; Omission error: 0.04/0.45 = 0.09			
Overall accuracy: 0.47 + 0.40 = 0.87; Kappa index = 0.74			

relatively simple RS methodology using a decision-tree approach. The GIS methodology had consistently higher overall accuracy, most notably in semi-arid regions. Where possible, the use of survey maps as a primary data source, supplemented by remote sensing, may lead to more accurate identification of built areas and improved quantification of urban expansion.

The use of each data set has distinct advantages and disadvantages, and we concur with other researchers that combining data sources holds the greatest potential for accurate assessments of land development (Foresman *et al.* 1997, Stefanov *et al.* 2001, Yang and Lo 2002, Mundia and Aniya 2005). The GIS approach described here is labour intensive, requiring substantial georeferencing, and digitizing of maps and/or primary source aerial photographs. Furthermore, the maps may be subject to human error and the comprehensiveness of updates may be compromised by limited funding (E. Shlomi, Survey of Israel, personal communication). Another important limitation of the survey maps is that land use, as defined by survey maps, may not adequately describe the actual land cover, as in the case where agricultural land lies fallow, or is covered with construction waste, greenhouses or plastic sheeting, or 'open' spaces are in fact parking lots.

However, the maps typically provide more historical depth, having been produced over much of the 20th century for many parts of the world. Furthermore, because maps are based on aerial photographs, there is little risk of confusing urban areas with sand or soils. Finally, the proportion of omission and commission errors in the GIS methodology was consistently between 25 and 35% and, importantly, the causes of the errors were predictable.

The RS analysis can be less work intensive than the GIS approach depending on the methodology used to differentiate among land-cover types (this process itself can be challenging and time-consuming). The decision tree used in the RS analysis is a straightforward method for characterizing land cover and illustrates limitations likely to be found regardless of classification methodology. Although higher accuracy may be possible with more involved techniques (e.g. textural analysis or temporal unmixing), the simpler method is more likely to be used by planners and resource managers with limited experience with remote sensing. Advantages of using the RS techniques include more readily accessible data, which are also available in real time. When defining built area, the RS analysis may be more reliable in urban settings, primarily due to being able to detect large impervious surfaces such as parking lots.

However, in rural settings Landsat TM data-based maps fail to identify low-density communities as built areas because pixels are often a mixture of built and vegetated land cover. Past efforts to discriminate between low-density residential areas using RS data have had mixed success (McCauley and Goetz 2004, Irwin and Bockstael 2008). Underestimation of built area in rural and suburban settings should be expected with RS analysis given existing approaches. RS identification of built areas is also subject to error when spectral properties of open space are similar to built space, for example, semi-arid regions (figure 7). Overestimation of built area (commission errors) in semi-arid regions with low vegetated cover should be expected with RS analysis.

Combining maps based on GIS and RS data compensates for the weaknesses of each data source individually. Researchers who rely on a Landsat-based RS analysis should pay particular attention to the types of developed land cover that are apt to be missed or underestimated by the analysis. This is a particular concern for suburban and rural development, which is fast growing in many areas (Irwin and Bockstael 2008). The RS data supplemented the GIS data by identifying three built land-cover types. First, the RS method detected areas that were functionally 'built' but were not structures, including cemeteries, airport runways, large structures (e.g. warehouses, hangars and shopping centres) and parking lots. An example of this is a sewage treatment plant (figure 8(*c*), (*i*)). Second, the RS method detected areas that had been built between successive publications of updated maps (figure 8(*c*), (*ii*)). Third, the RS method detected areas that were built but were unintentionally or intentionally excluded from maps (figure 8(*c*), (*iii*)).

Landsat data have been shown to be effective for urban change detection in several analyses (Ward *et al.* 2000, Stefanov *et al.* 2001, Zhang *et al.* 2002, Xian and Crane 2005, Yuan *et al.* 2005). To control for some of the heterogeneity in determining amounts and patterns of change using large satellite data sets, researchers can focus on smaller areas immediately around built areas, thereby eliminating some landscape variability. However, as spatial scales of analysis becomes more focused, survey maps become increasingly attractive as a primary data source.

Our GIS method identifies a greater amount of built area undetected by the RS method than the reverse, and so we advocate beginning an analysis of urban LUCC with thematic maps whenever available at the desired spatial scales. In this comparison, the RS method underestimated the amount of built land cover in rural areas (e.g. the Sharon region) by up to 75% as compared to the GIS method (figure 5).

Researchers and practitioners can avoid systematic underestimations of built area by combining data sources and exploiting the strengths of each data source to offset the weaknesses of the other. Our combined map provides a more realistic estimate of built area in that it includes rural and suburban development, censured data and impermeable surfaces that may have been overlooked by relying on a single data source. As suburban and exurban sprawl becomes more pervasive, the need for increasing accuracy by combining data sources grows.

Ultimately, the choice in data sources for the detection of patterns of expansion of built space depends on the desired temporal and spatial resolution and the scale of the analysis, as well as the technical limitations of the researchers or practitioners. This research draws attention to specific land-cover types that may be misclassified when using either survey maps or satellite data. It is important that researchers be aware of the potential differences in results that can be generated from different sources and even more importantly, circumstances in which we may be over- or underestimating built space using only RS data.

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