Article

Planning and Design

Environment and Planning B:
Planning and Design
2016, Vol. 43(5) 848–870

DOI: 10.1177/0265813515598991
epb.sagepub.com

The connectivity of Haifa urban open space network

Marina Toger
Faculty of Architecture and Town Planning, Technion—Israel Institute of Technology, Israel

Dan Malkinson
Department of Geography and Environmental Studies, and The Golan Research Institute, University of Haifa, Israel

Itzhak Benenson
Department of Geography, Faculty of Humanities, Tel Aviv University, Israel

Daniel Czamanski
Faculty of Architecture and Town Planning, Technion—Israel Institute of Technology, Israel

Abstract

Urban open spaces are considered as spatial residuals of the expansion of built areas. The environmental impact of the resulting land-cover pattern and associated ecosystem services are frequently evaluated at a crude spatial resolution only. However, wild animals use remaining interconnected fine-grain open spaces as an infrastructure for movement.

In this paper, we traced the evolution of an open-space system in Haifa, Israel, and examined the impact of urban morphology on size and distribution of open spaces at different spatial resolutions.

At a 30 m resolution, our analysis indicated fragmentation and increasing partial elimination of open spaces. Over time the connectivity declined at a diminishing rate, yet the network did not disintegrate into separate components. The evolution analysis implied that in crude resolution, the open space network is threatened.

At a 5 m resolution, our analysis showed that Haifa remains porous to animal movement. Using combined multiple least-cost paths through the urban landscape of heterogeneous permeability, we illustrated extensive connectivity among open spaces. Backyards and other urban in-between spaces complemented the seminatural open-space network connectivity, enabling wildlife movement between habitat patches and thus survival in an urbanized environment.

Keywords

Urban, open space, network, morphology, dynamics, connectivity

Corresponding author:
Marina Toger, Technion—Israel Institute of Technology, Technion City, Segoe building, 510, Haifa 3200003, Israel.
Email: marinat@technion.ac.il

Introduction

The apparent disappearance of urban open spaces is of great concern to urban planners. The common perception is that city expansion swallows all open spaces unless duly protected. Indeed, analyses at crude spatial resolutions indicate that urban open spaces are disappearing, except for large-scale planned projects (e.g., Central Park in New York City, Copenhagen's Green Fingers). However, when cities are examined at a finer scale, additional open spaces are revealed and the porous structure of cities becomes evident. The pores include planned and unplanned open spaces. Planned open spaces consist of public parks, lawns, and gardens, sport and recreation facilities, and other dedicated open land uses. Unplanned open spaces include unbuilt, vacant and abandoned lots, wastelands, fallow and abandoned agricultural lands, creeks and ravines, flood plains and riverbeds, coastlines, wetlands, roadside vegetation, backyards, and other unbuilt patches of land.

Urban open spaces are increasingly part of the public discourse and motivate various planning efforts (Maruani and Amit-Cohen, 2007). Yet, there is relatively little scientific knowledge concerning their abundance, morphology, and dynamics. There is empirical evidence that wildlife and native plant species inhabit these pores in the urban fabric (Matthies et al., 2013; VanDruff and Rowse, 1986). Furthermore, there is ample informal evidence, such as reports of urban residents of frequent sightings of various wild animals. For example, in Haifa, Israel the wild boar population grew so large that the municipality is implementing measures to control their numbers (Barshaw, 2012). Similar phenomena are observed in other cities, such as Berlin and Barcelona (Licoppe et al., 2013). The existence of relatively large open-space patches, within and outside the city, with corridors linking them to smaller patches enables wild species to move within the urban environment despite observed fragmentation of the system of open spaces (Goddard et al., 2010).

The presence of wildlife in cities in contradistinction to urbanization-induced disappearance of vegetated urban open spaces is the focus of this paper.

This paper aims to answer the following questions:

- How does urbanization affect open-space system connectivity?
- Can open-space systems in cities support wildlife movement?
- What geographic resolution is relevant for analysis of open-space connectivity and wildlife movement?

This study examines urban open spaces in Haifa as a functioning network that facilitates movement and thus contributes to the persistence of wildlife populations in cities. To this end, based on a temporal series of aerial imagery, we mapped and analyzed changes in amount of the urban open spaces and spatial relationship among them. The citywide open-space system was translated into a network of interconnected patches at a resolution of 30 m. In addition, we performed a high-resolution (grain size of 5 m) study of the connectivity of urban open spaces based on a mapping of land-use/land-cover types in Haifa.

The crude-resolution analysis indicated the urbanization-induced decrease in overall area and network density of the open-space system. The high-resolution analysis showed that contribution of an individual open-space patch to the overall connectivity depends on the following factors: the patch area; distance to and amount of other open spaces; the land cover of other patches in the vicinity; and urban morphology type in general. The analyses indicated that Haifa open-space system seems better connected than one might expect.

The remainder of this paper is comprised of five sections. The next section presents a brief sketch of existing knowledge concerning the evolution urban built and open spaces. The third section contains a crude-resolution analysis of the temporal changes in Haifa's open-space system. In the fourth section, we present a finer-resolution analysis of inter-patch connectivity structure. Conclusions and discussion are presented in the final section.

Spatial evolution of cities and urban open spaces

Urban open spaces often are the residuals of spatial expansion of the built environment. The evolution of the built areas in cities is the result of self-organization processes circumscribed by land-use plans and incremental efforts to change them. Any attempt to understand urban ecosystems must contemplate fundamental questions concerning the spatial coevolution of social and natural systems and feedback processes that govern them (Alberti, 2005; Hobbs et al., 2013; Winder et al., 2005). Although both are embedded in a dynamic biophysical environment, agreement concerning a common coevolutionary framework remains unresolved (Gual and Norgaard, 2010; Helbing et al., 2009). For decades, urban geographers, urban economists, regional scientists, and ecologists ignored each other and the interdependence of these processes (Czamanski et al., 2008). Extant knowledge is incomplete and often misleading.

According to the classic monocentric urban model (Alonso, 1964; Mills, 1972; Muth, 1969), the spatial structure of cities is governed by competition for accessibility to the city's center. As population grows, the model implies a process of sprawl from the center outward as a uniform wave engulfing and removing all open spaces. While the model generated many useful insights concerning cities, its validity has been established at a very crude spatial resolution only. Nevertheless, the planning discourse is colored by its findings. In reality, cities display a polycentric structure that evolves by leapfrogging (Bettencourt and West, 2010; Ewing, 2008; Frenkel and Ashkenazi, 2008), resulting in a relatively dense urban core and porous areas of varying density.

At the broadest level, the lack of agreement between theories and evidence is due to the inconsistency of the spatial and temporal resolution of theoretical and empirical analyses. Theories generally refer to reality in broad-brush fashion using crude, stylized facts. Heterogeneity of cities and their environments is overlooked in the scholarly literature that is based on behavior of typical agents and per-capita or per-unit indicators, focusing on common traits to various places and coarse-scale classifications (Cadenasso et al., 2007). Accordingly, various phenomena are viewed in terms of linear relationships to size with average dynamics common to all places. However, these relationships are the result of sublinear or superlinear relationships and local emergent processes (Bettencourt and West, 2010). A growing body of empirical evidence suggests that spatial dynamics reflect scaling laws that are place specific (Benguigui and Czamanski, 2004; Benguigui et al., 2000).

There is evidence that the quantity of urban open spaces is shrinking (Orenstein and Hamburg, 2010; Shoshany and Goldshleger, 2002). Nevertheless, some open spaces remain within cities (Tardin, 2012). There are good reasons for the persistence of open spaces within the porous urban spatial structure. As urban expansion often happens by leapfrogging, city fabric features built-up clusters with open spaces in between. Some of the gaps fill in during later stages and others gain protected status or remain undeveloped. Furthermore, urban open spaces generate benefits for human quality of life, health, and well-being (Bolund and Hunhammar, 1999), resulting in willingness-to-pay for proximity to open spaces. Newer models of urban growth presume that land developers take the demand for proximity to open spaces into account, and their profit-maximizing behavior exploits planning restrictions and resulting land prices to develop noncontiguous land parcels (Broitman and Czamanski, 2012; Czamanski and Broitman, 2012). These models reject equilibrium conditions. They reflect self-organizing dynamic processes and present urban open spaces in a constant state of flux. However, heretofore only some feedback effects have been considered.

With urban and agricultural land uses consuming increasing amounts of land, urban open spaces remain an important haven for native flora and fauna (Hobbs et al., 2013). Networks of open spaces, made-up of large and small patches and corridors linking them together, enable wildlife populations to persist (Goddard et al., 2010). Contrarily, allowing wildlife into residential neighborhoods generates negative externalities, and it is unclear to what extent these externalities affect urban spatial dynamics. Tardin (2012) argues that urban and peri-urban open spaces should be analyzed as an interconnected infrastructure system optimized to fulfill human demands for recreation and amenities together with environment conservation targets.

In this paper, we illustrate changes in amount and connectivity of open spaces in Haifa, Israel.

Crude-resolution analysis of Haifa's open-space network

Haifa is located on the slopes and at the foot of Mount Carmel, on the coast of the Mediterranean Sea (Figure 1). It is the third largest city in Israel with a population of 270,000. The estimated population of its metropolitan area is more than million people (Central Bureau of Statistics, 2009) and it covers 65.2 km^2 (Haifa municipality, 2012).

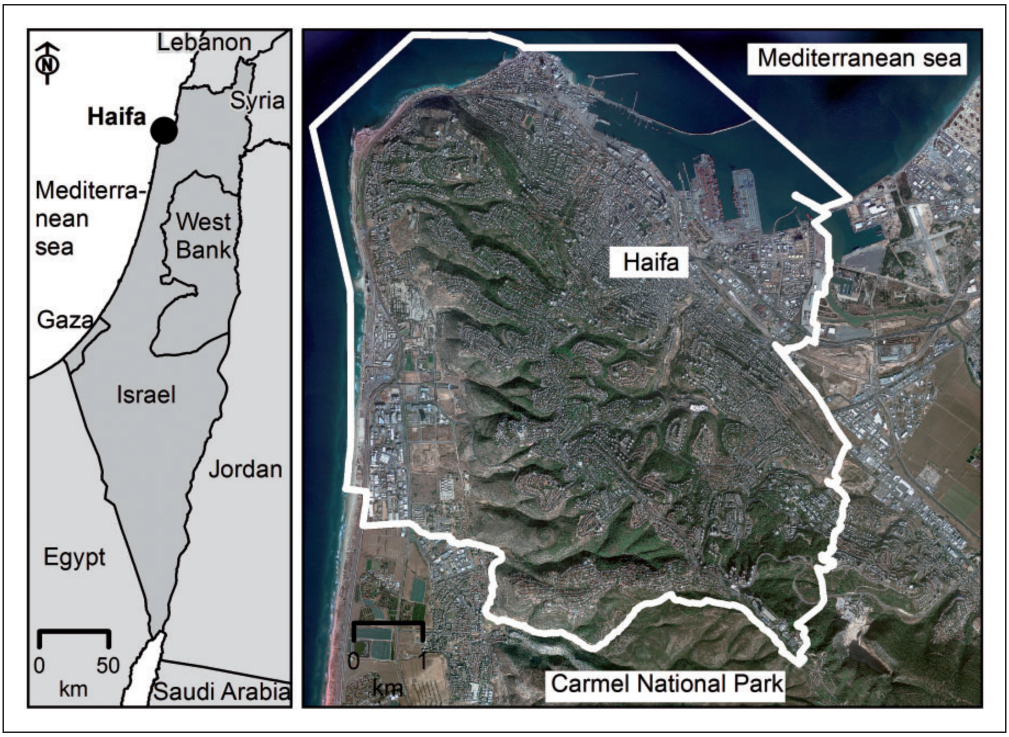

Figure 1. Study area location. Note the large vegetated open-space area to the south of Haifa, the Carmel National Park.

The mountainous topography of the city includes ravines (wadis) that penetrate deeply into the urban built fabric. These wadis, formed like green fingers, comprise the backbone of the urban open-space system. The seminatural open spaces in and around Haifa mostly consist of rocky slopes, covered with typical Mediterranean scrubland and woodlands, and patches of herbaceous vegetation. The seminatural forest remnants contain maquis vegetation communities interspersed with planted pine-tree stands.

For the initial crude-resolution analysis, we utilized open-space mapping data set (Balter, 2010) based on a set of digital aerial photos and historical maps. Photos for 1945, 1962, 1986, 1999, and 2004, were at scales of 1:50,000–1:20,000. Additionally, we mapped open spaces for 2010 at 1:12,000.[1] For the purpose of this analysis, open spaces were defined as vegetated nonpaved patches of open land and not used by modern, monoculture agriculture, larger than 100 m^2. The open spaces comprised 66% of the total land area in 1945 and decreased to 37% by 2010. The analyses were carried out using ArcGIS10.1 software (Environmental Systems Research Institute [ESRI], 2012), NetLogo5 (Wilensky, 1999) for the network construction and Gephi (Bastian et al., 2009) for network analysis and visualization.

Using an approach comparable to Urban and Keitt (2001) and Morgado et al. (2012), the open-space patterns were transformed into a network using a threshold aerial minimal distance between patch edges of 60 m. This distance is below the mean daily movement distance of most of the mammal species observed in Haifa. Any two patches whose edges are at a distance below 60 m are defined as connected.

Figure 2 illustrates the diminishing connectivity that resulted from the growth of Haifa. Open spaces, are depicted in green in the first and third rows. All other land-cover types are in white. The second and fourth rows show the corresponding networks for each sample year. The patches are shown as nodes and connections between them as edges. Node size depicts normalized patch area and node color indicates gradation of the betweenness centrality network metric, ranging from central nodes that are shown in green to peripheral nodes in red with intermediate values in yellow. Betweenness centrality indicates the importance of a node for overall network connectivity Urban and Keitt (2001). Most large open spaces featured high betweenness centrality values.

It is evident that increasing urbanization caused changes in the network of open spaces. Figure 3(a) shows the evolution of the number of open space patches, number of connections among the patches, termed links, and number of connected patch clusters, termed components. All three numbers increase during 1945–1999, indicating fragmentation of the open spaces due to expansion of built-up areas and roads. From 1985, these numbers stabilized indicating that the fragmentation process stopped.

Figure 3(b) indicates the decline in network density over time. It is measured as the percentage of links present in the network to maximal number of links possible. This number indicates that despite the initial increase in number of network elements, the connectedness of the network deteriorates over the entire period. Figure 3(c) indicates the decrease in total area of the largest (giant) component of the network. Over the entire period, the giant component included all the largest patches and was connected to the core vegetated area (Carmel Forests, the vegetated open area south of the city, see Figure 1, lower right). Patches that do not belong to the giant component are disconnected from the network, are small in area, and thus are not important for the network. The giant component area as well as percentage of the total open-space area decreased during 1962–1999, indicating that parts of the open-space network were converted into built areas. It is noteworthy that changes in the system and the process of fragmentation in particular seem to have diminished by 2004. This is apparent from all the above indicators, in particular from changes in the number of open patches and links in the city.

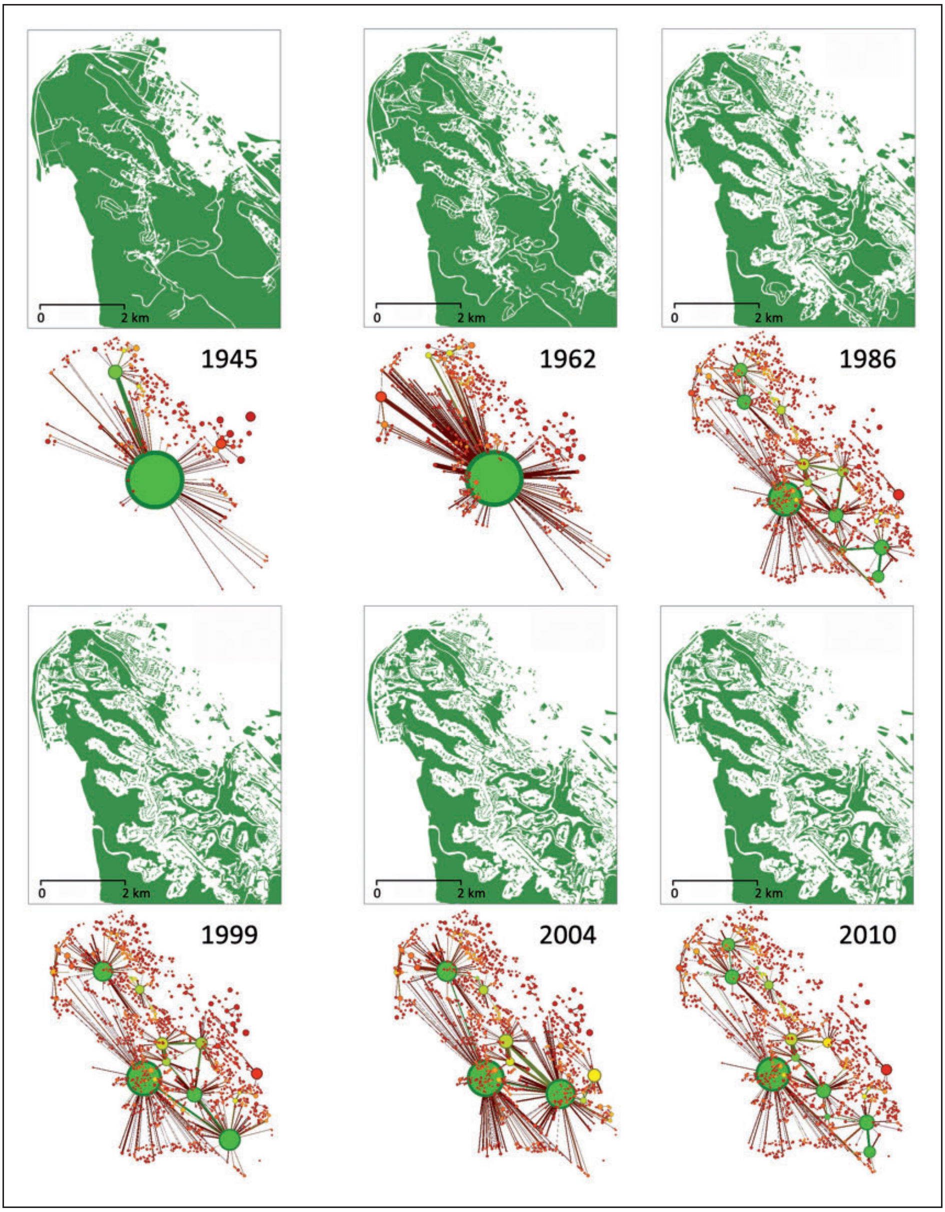

Figure 2. Crude-resolution mapping and schematic network representation, 1945–2010.

The above crude network analysis suggests that the dynamics of the open-space pattern in Haifa is consistent with the assertion that urbanization results in the significant reduction in open-space area (Orenstein and Hamburg, 2010; Shoshany and Goldshleger, 2002). Indeed, Haifa's initial built-up seed of 1945 had almost continuous open space around it. Later development claimed fingered areas with mild slopes and left steep areas unexploited. These areas were then incorporated into Kaufmann's plan as protected open space land use (HP, 2009). Afterward, the fingers were cut into fragments and patches, and finally, many fragments were eliminated during the first decade of the 21st century. The decline of

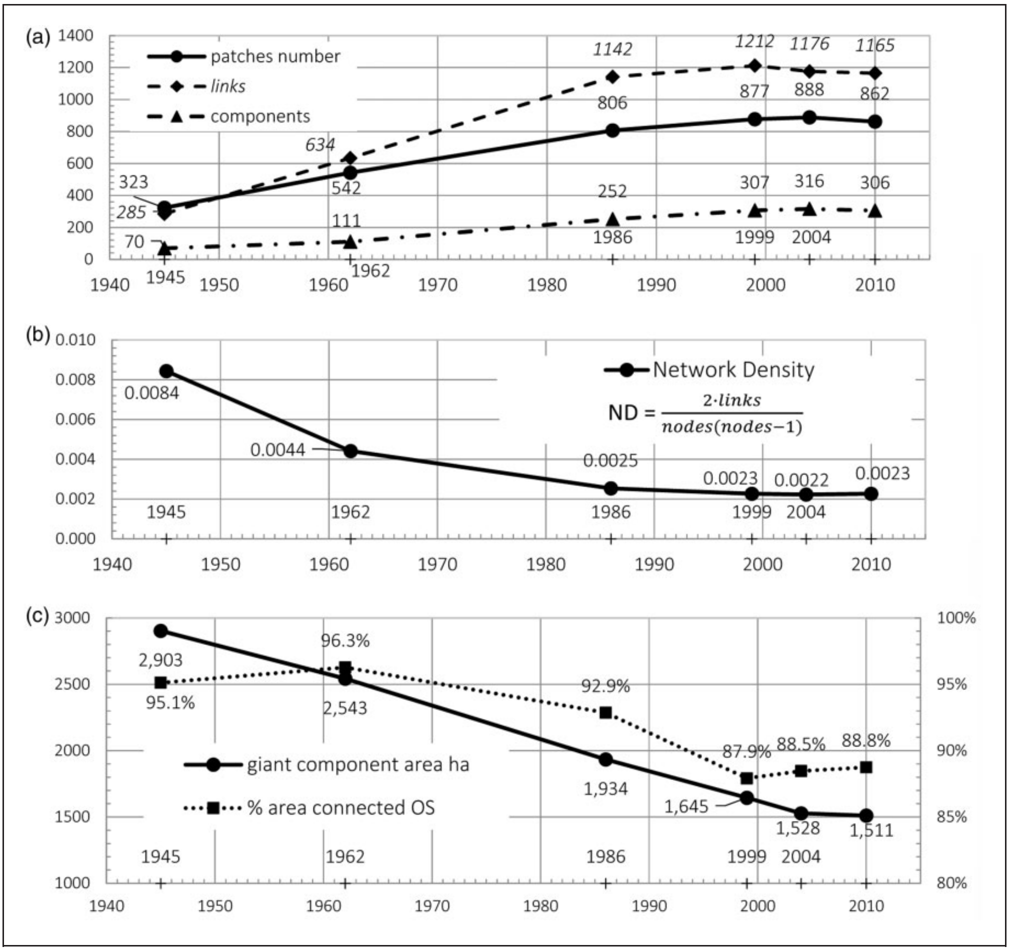

Figure 3. Dynamics of the number of open-space patches, links, and components (a), network density (b), connected area size and ratio out of total open-space area in Haifa (c).

the giant component area indicates the deterioration of the total connected habitat area. The percentage of connected area first declined, but then increased, indicating that the open-space patches that have been eliminated after 1999 were mostly already disconnected from the main network. Another possible explanation is that during 2004–2010, small patches were eliminated due to development of these patches.

High-resolution patterns of open-space connectivity

The above structural analysis does not present the full picture of the processes taking place. This is evidenced by a comparison of crude 30 m and fine 5 m resolution studies for 2012.

For the high-resolution analysis, we used a 2012 aerial orthophoto of Haifa metropolitan area with a pixel size of 0.25 m. We performed manual interpretation at various levels of accuracy and selected 5 m as benchmark for the entire data set. We used ArcGIS10.1 (ESRI, 2012) with Feature-Analyst and Python scripting for data preparation, interpretation, and analysis. The aerial image was manually classified into a polygon layer of 20 land-use/

Table 1. Land-use and Land-cover classification and resistance values.

Land-use/ land-cover type	Description	Cost	Category
Forest	Seminatural and planted forests and woodlands	0.001	Open spaces
Shrubs	Mediterranean scrubland		
Grassland	Herbaceous vegetated areas, burnt land, grasslands		
Orchard	Vineyards, orchards	0.1	Transit areas with varying resistance
Garden	Managed vegetated areas: parks, gardens, lawns, sport facilities, monuments, recreation	0.25	
Wasteland	Garbage, dunes, beach, mines, wasteland open areas		
Fallow	Abandoned and fallow fields		
Field	Agricultural cropland and cultivated open areas	0.5	
Dirt road	Unpaved roads		
Trail	Paved or unpaved footpaths and trails		
Backyard	Backyards, squares, logistic spaces around buildings		
Transportation	Railroads, parking, transportation logistic space, airports, seaports	0.75	
Roads	paved roads		
Construction	Construction sites	∞	Obstacles
Industry	Industrial areas, cemeteries, prisons, exurban commercial areas		
Built agriculture	Greenhouses, warehouses		
Water	Water bodies		
Buildings	Building footprints		

land-cover types (Table 1). The vector polygons were rasterized based on majority rule, into 5×5 m raster. We have randomly chosen 50 locations on the classified map of 2012 for validation. For 30 locations, we were able to validate our classification by comparing to the Google Street View images (Google maps, 2012). For the other 20 cases, we visited the locations. In all cases, the classification was correct.

Although the total sum area of open spaces was approximately the same (17.82 km^2 for crude resolution and 17.84 km^2 for fine resolution), the high-resolution mapping reflects a somewhat different landscape structure. At a resolution of 5 m, more patches are discernible (Figure 4). Distances among patch borders are shorter with more patches in between, resulting in higher connectivity. At high resolution, the largest patch had a bigger area (1.63 km^2 vs. 0.75 km^2) indicating that patches that seemed disconnected are actually connected. Even using a simple binary patch-matrix mapping increasing resolution indicates higher open space connectivity.

In addition to their intrinsic value, open-space networks in cities can enable animal movement. The possibilities of movement are defined by small-scale heterogeneity of open spaces in respect to connectivity to the surrounding animal habitats. The consequences of habitat fragmentation can be understood at a resolution of animal movement decision at the scale of passages between fences or vegetation patches.

Much of Haifa conforms to the Garden City planning framework. The basic planning unit is a parcel. A typical parcel zoned for construction has a Building Limit Frontier of at

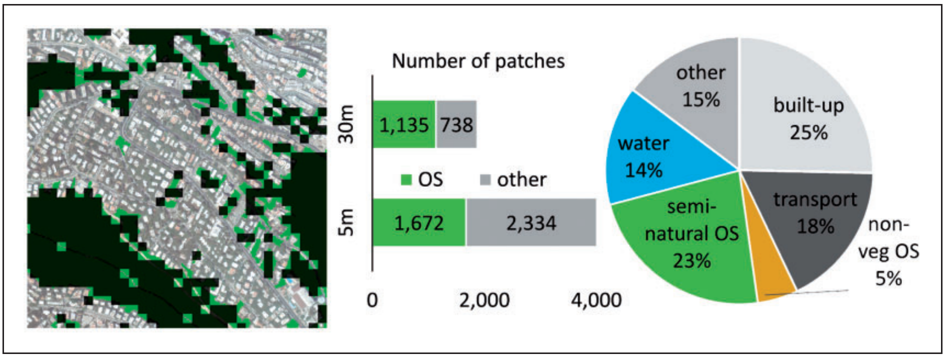

Figure 4. Crude and fine resolution patch analysis. Left: Mapping at crude (dark green, 30 m cell size) and fine (green, 5 m cell size) resolution. Middle: Number of contiguous patches detected at crude 30 m (top) and fine 5 m (bottom) resolutions, open spaces (green) and other land-cover types (gray). Right: Land-use/land-cover composition of the study area, 2012.

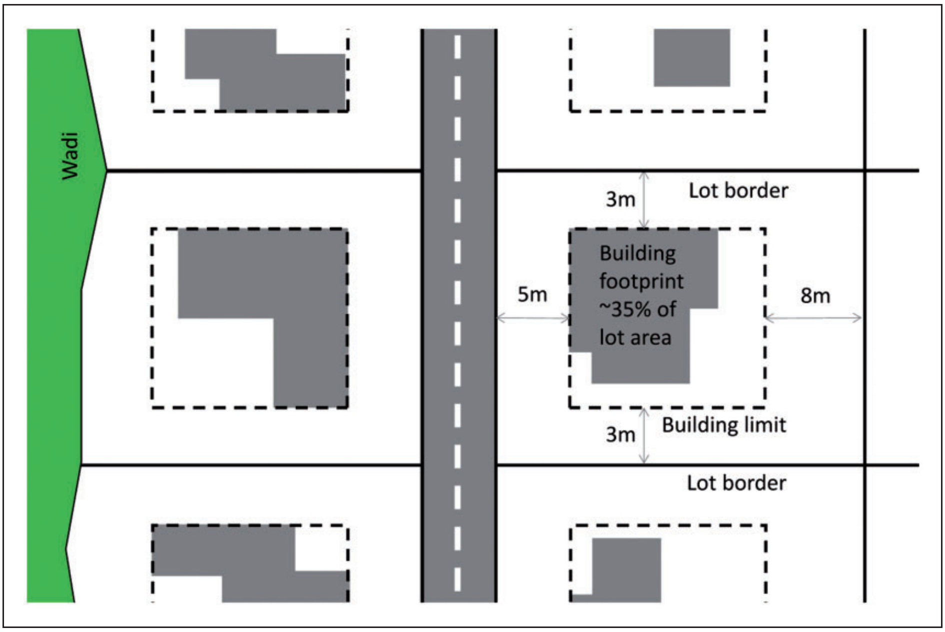

Figure 5. A typical parcel plan with the Building Limit Frontier marked.

least 5 m distance from the front and 3–5 m from the side plot boundaries (Figure 5). Thus, we chose the 5 m cell as a unit for analysis.

In addition to buildings, plots include paved areas, parking lots, and backyards. Furthermore, depending on the plot's geographic location, minimal unpaved area for a residential parcel is required to be 25–50% of its size in order to get the building permit. Parts of the parcel left unpaved typically are gardened or recolonized by ruderal vegetation.

The amount of the unbuilt open space inside a parcel depends on the development type. For instance, high-density modern development contains less open spaces than the long rectangular 5-storey housing projects of the 1960s. High-resolution mapping of the city indicates that each urban parcel contains spaces that are impermeable to animal movement and permeable spaces around the buildings. The specific patterns of permeable and impermeable spaces result from particular ways that the cities are built. Thus, while crude-resolution analyses, based on land-use maps, consider the entire built-up parcels as impenetrable, at finer resolutions penetrable spaces are discernable inside almost every parcel (not considering terraced walls and fences). Some of these can serve as corridors for traversing among larger patches. Their traverse-ability depends on overall width, number/density of paths, and amount of bottlenecks. Furthermore, in Haifa, many residential parcels directly border vegetated seminatural areas and are not fenced off. Thus, the city is connected to animal habitats outside the built areas. Moreover, the resolution of 5 m is suitable to analyze the urban morphological differences relevant to connectivity of medium- to large-sized mammals.

By means of a representative sample of built-up areas from the rich Haifa land-use/land-cover database, we tested various methods for identifying traversable corridors. The Indian Crested Porcupine (*Hystrix indica*) was chosen as an example species. We chose the Indian crested porcupine out of the species that we had observed using cameras[2] for the following reasons: the porcupine is more sensitive to human disturbance than golden jackal or wild boar; the porcupine prefers seminatural vegetated land cover; porcupines are herbivores and thus less dependent on urban food resources; the porcupine is sensitive to habitat area and landscape connectivity; there were enough observations to deduce the presence of porcupine population in Haifa; the Indian crested porcupine is not overabundant in Haifa and currently is not considered as a nuisance.

In what follows, we apply Rudnick's et al. (2012) understanding of the cost of animal movement in the city, namely as combined measure representing disturbance from human activities (perceived risk of movement) and energy expenditure of the animal. Operational estimate of the cost-of-movement for least-cost-based connectivity analysis is widely debated (Spear et al., 2010). Most papers apply as a cost the inverse of habitat suitability index or cost estimates that are based on expert opinion. For this paper, we relate resistance to the land-use/land-cover type, the most frequently used environmental variable in connectivity analysis studies (Zeller et al., 2012).

Habitat suitability index calculations are based on the habitat functional features in the patch and/or occupancy empirical data for the focus species (Spear et al., 2010). Roads and built areas are scored as unsuitable for porcupine habitat in coarse-scale analyses. Occupancy data per land-cover type is nonexistent for porcupines in cities. Therefore, we used occupancy observation-based index for open spaces and agriculture in the North of Israel, areas with similar climate and vegetation cover to Haifa (Naali, 2009). For the rest of land-cover type resistances, we used expert opinion.

For the porcupine, resistance values based on Naali's (2009) species-specific index of traverse-ability were calculated as ~0/m for natural areas and 0.01 for olive groves. To avoid computational problems due to division by zero and also because the seminatural open spaces in Haifa contain a blend of maquis vegetation with olive and pine trees, the approximate resistance values for the seminatural areas and olive groves were chosen as 0.001/m, 0.1/m for orchards, and 0.25/m for fallow crops areas. For other land-cover types, based on expert opinion, we assumed that the cost of crossing a backyard is 0.5/m, twice as hard as crossing a fallow agricultural field, while crossing a road cost 0.75/m, buildings and obstacles had infinite cost. The landscape was classified into 20 land-cover types with resistance values accordingly (Table 1).

The connectivity of patches was estimated using the least-cost-paths over a resistance surface. It is well known that animals have essential random component in their route choice and use different paths with change of seasons, weather, or time of day. Formally calculated single least-cost path not necessarily reflects the path used by the animals (Sawyer et al., 2011). To reflect possible variations, instead of the least-cost path, we consider *all possible* paths between two patches with a cost per the unit of a path length lower than a given threshold per-unit cost C*.

Given C*, some urban areas allow wide navigation corridors, while the others enable only dispersed multiple narrow paths through them. Wider corridors can be used both by species that tolerate proximity to disturbance (e.g., wild boar) and by those that do not. The wider corridors enable usage by a wider range of species (Hilty et al., 2006). The connectivity for a certain species can be determined by adjusting the model parameters: landscape resistances and cutoff values of minimal corridor width and maximal corridor path-cost C*.

The detailed description of the corridors detection method is presented in Appendix 1.

In what follows, we estimate corridors and propose four measures for characterizing the patterns of corridors between two habitats (Figure 6):

n Number of movement paths between patches
w Width of bottleneck, i.e. width of the narrowest part of the corridor, in meters
r Percentage of the area covered by the corridors out of the entire nonopen area analyzed
q Percentage of the area of the widest corridor out of its convex hull.

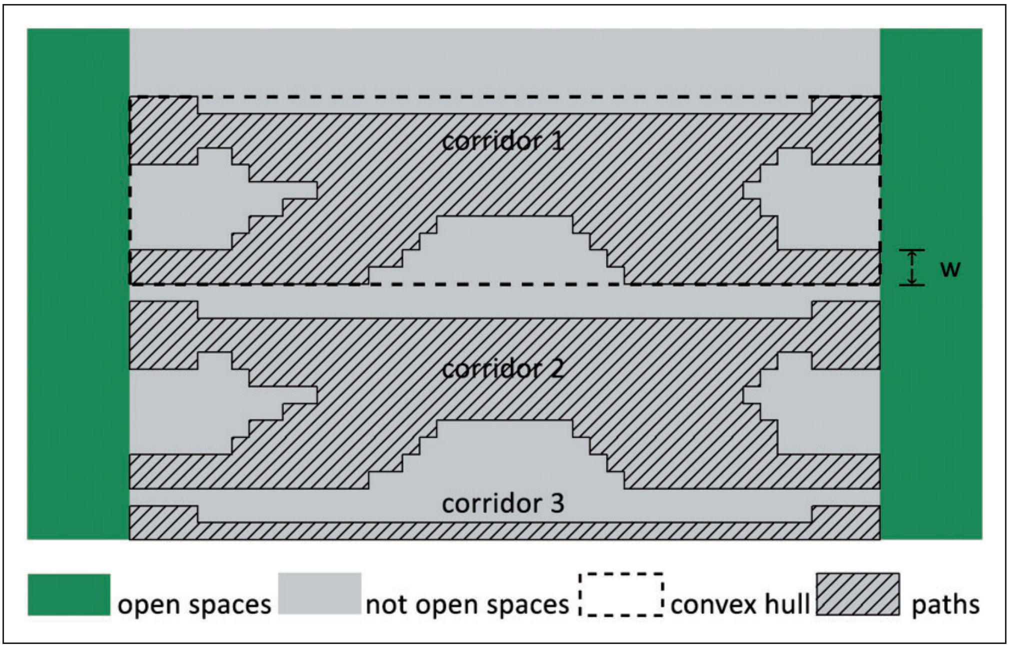

Figure 6. Explanation of corridor metrics. Let the green patches at the left and right be connected by three corridors. For these corridors' pattern and C* = 130/m: Number of movement corridors $n = 3$. Width of bottleneck $w = 10$ m. Percentage of the corridors sum area (hatched) out of the entire nonopen area (in gray). In the example above corridors' area is 15,300 m^2, while total nonopen area is 33,000. The ratio $r = 15,300/33,000 = 46\%$. Percentage of the area of the widest corridor out of its convex hull. In the example above the widest top corridor area is 7975 m^2 and its convex hull area is 11,000, thus $q = 7975/11,000 = 73\%$.

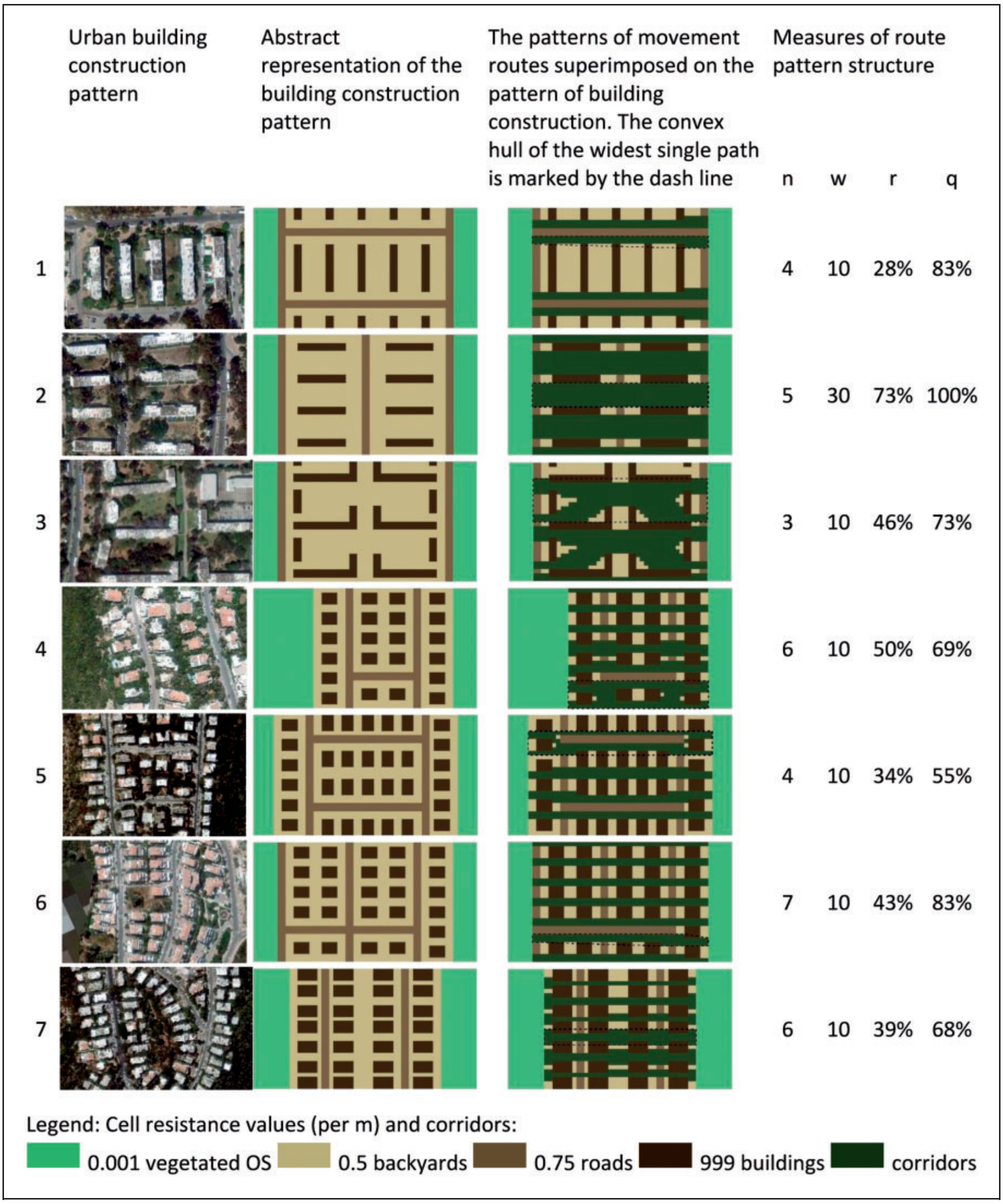

Figure 7. Patterns of movement routes between two green areas at a distance of 280 m for different construction patterns and the threshold cost $C^* = 130$.

Different urban patterns entail distinctive corridor patterns. To illustrate, we chose seven representative samples of Haifa residential neighborhoods and estimated movement corridors for each of them (Figure 7). The dimensions of buildings, roads, and unbuilt areas were measured from the aerial images of Haifa. Samples 1–3 represent the typical development of late 1960s, featuring long 5-storey buildings. Samples 4–7 represent the "Garden city"-type residential neighborhoods with freestanding buildings of three to five floors and varying gap sizes and block orientations.

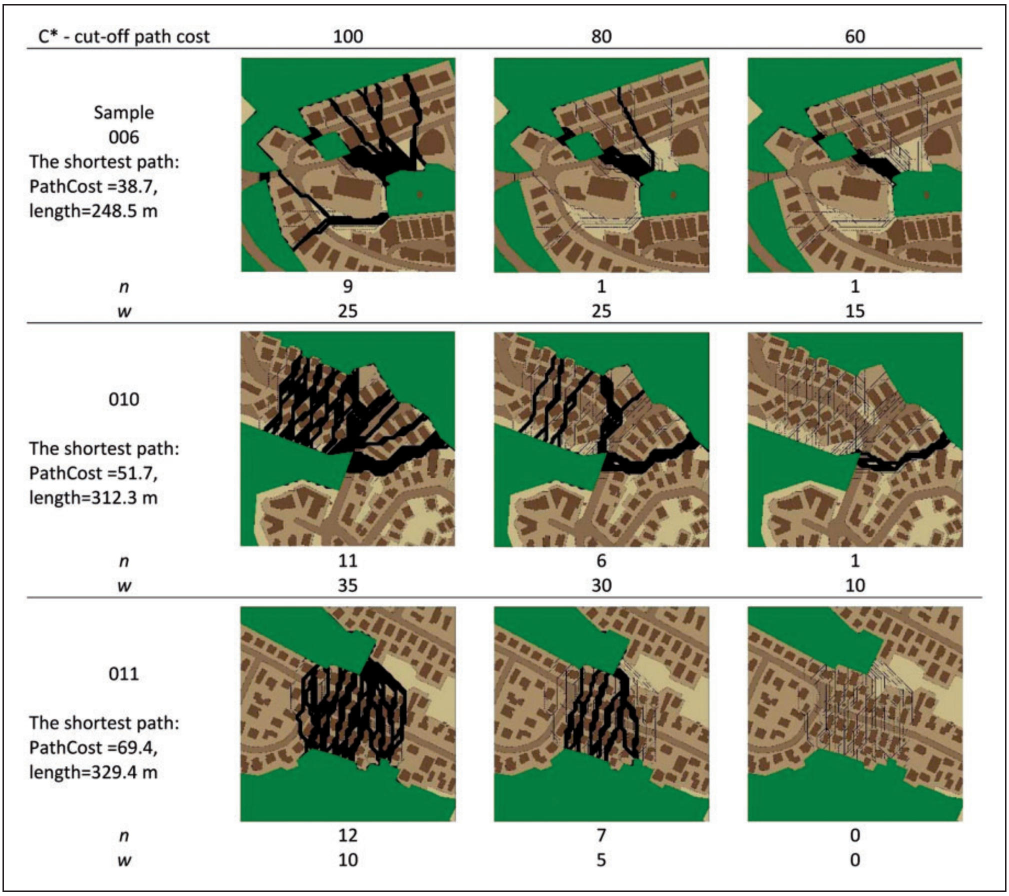

Figure 8. Three samples with corridors detected through the urban matrix. Each row represents different urban patterns (samples 006, 010, 011). The columns correspond to the different cutoff path costs ($C^* = 100$, 80, 60).

To illustrate the variety of movement patterns in a real landscape, we compare the resulting patterns (Figure 8) for three distinct samples in Haifa with threshold costs $C^* = 100$, 80, and 60. At $C^* = 100$, the corridors contained many redundant paths, at $C^* = 60$, minimal connectivity was observed, and the value of $C^* = 80$ seems a plausible compromise between the extremes. Figure 8 indicates the minimal shortest path cost and length for each sample. For each pattern and threshold value, n—number of distinct corridors was calculated (with cost lower than C^*) and w—the widest corridor (width of the bottleneck in all the corridors). In Figure 8, paths with path cost below C^* are indicated by fat black lines.

Increase in C^* led to a stepwise increase in n and w metrics for all samples (Figure 9).

In Figure 10, we present analysis of connectivity for a single patch inside the Denya neighborhood in Haifa.

Our approach yields several corridor patterns (Figure 10): parallel thin multiple paths between buildings (1 and 2), short and wide corridor (3), wide multiple paths (4), and corridors with a stopover (5, 6). The small stopover patches of undeveloped land with seminatural vegetation are important for connectivity. In case of corridor 6, development

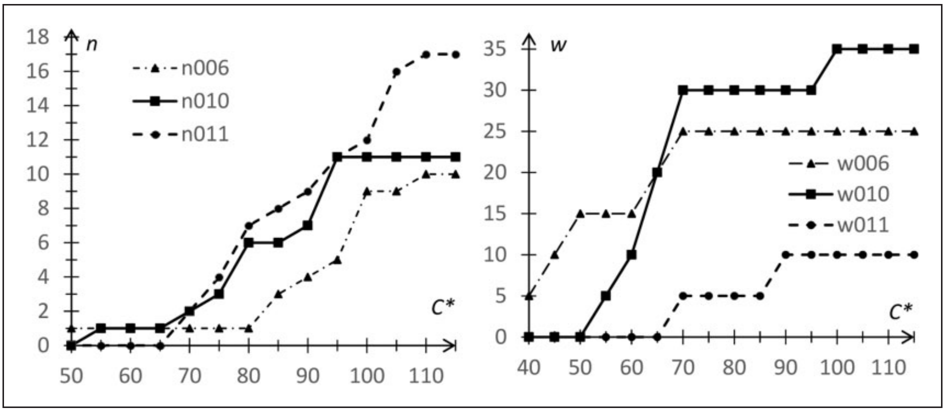

Figure 9. Number of paths *n* (left) and their bottleneck width *w* (right) corridor metrics (ordinate) plotted against the increasing cutoff path-cost C* (abscissa). Each line represents a different sample of the urban pattern (samples 006, 010, 011, Figure 8). Both *n* and *w* characteristics grow with an increase in the cutoff path-cost C*.

Figure 10. Connectivity analysis for an open-space patch (center) in Denya neighborhood (C* = 200).

of the stopover patch will destroy the whole corridor. The overall picture suggests that this patch is well connected to the surrounding open spaces and potentially can be utilized by animals. Indeed camera and field observations indicated presence of wild boar, jackal, porcupine, and mongoose.

Conclusions and discussion

Open spaces in cities function as an interconnected system (Tardin, 2012). Research on whether urban open-space systems can support wildlife movement has been implemented using open-space connectivity analyses (e.g., Kong et al., 2010).

In this paper, we traced the evolution of open-space system inside and at the fringes of Haifa, Israel. We illustrated the connectivity of urban open spaces at the citywide level and its changes over time. We used a connectivity analysis by threshold distance, a method analogous to Urban and Keitt (2001), with addition of the temporal comparison. At the crude 30 m resolution, few open spaces were detected and the resulting network appeared fragmented and scarce. The open-space system underwent fragmentation and subsequent partial elimination of its elements. The network connectivity diminished with time, albeit at a slowing rate. Despite that, most open-space patches remained connected to the main network component.

For the purpose of crude-resolution analysis, the landscape patches were categorized as either open space or matrix. However, urban matrix heterogeneity influences landscape connectivity. Least-cost-path open-space connectivity analyses incorporate landscape heterogeneity using landscape resistances (e.g., Kong et al., 2010). Pinto and Keitt (2009) criticized single least-cost-path analyses for ignoring alternative paths, and used multiple shortest paths stochastic approach. In contrast, rather than including a stochastic component, we achieved multiple shortest paths by detecting all paths with costs lower than a path-cost threshold. We also used finer resolution and more detailed land-cover classification.

At the fine 5 m resolution, more open-space patches were discernible, and the network was richer in connections. Using least-cost-path analysis, we illustrated by means of several samples how the urban matrix heterogeneity resulted in the complex structure of open-space connections. The combined multiple least-cost-path corridors included many redundant paths, that simple least-cost-path analyses often overlook, and thus reduced sensitivity to uncertainty in parameters.

Multiple paths included here provide alternate connection routes as can be discovered at this resolution of input data. In reality, we expect that small obstacles (e.g., fences), indiscernible at this level of resolution analysis, might cancel some of the paths and thus inhibit connectivity. However, additional paths might be discernable at higher resolutions. We mapped large obstacles, such as retaining walls or big fences, during the land-cover classification. Smaller obstacles, indiscernible in the aerial imagery, were observed in the field to have occasional gaps and holes, and fences were found broken in places by vandals and wildlife (wild boars). We accepted this limitation to the remote sensing technique without extensive fieldwork mapping. Thus, local analyses with mapping of obstacles at higher resolution using field surveys are advisable in key areas.

Nonetheless, the general pattern of corridors can be detected by this analysis. We used multiple paths to comprise each corridor in order to minimize the effect of local small obstacles on the analysis results, as well as to account for uncertainty in the route optimization target function and errors in data processing.

Backyards and other urban in-between spaces complemented the seminatural open-space network connectivity, enabling wildlife movement between habitat patches. Distinct open-space connection patterns derived from diverse urban tissues. For instance, we compared two patterns of residential development: the late 1960s train building blocks *versus* "Garden city" smaller houses. The first pattern features larger gaps between buildings with potential for wider green corridors. However, the connectivity was weaker in areas where the same building blocks were oriented perpendicular to the main movement direction between large open-space patches. Therefore, not only the development type is important but also the pattern orientation relative to the surrounding open spaces. Moreover, the amount of backyard vegetation varied among samples of the same morphological type. Thus, for future research, we would recommend to incorporate a vegetation index into the calculation of resistance values. This would add to the accuracy of the results without significantly changing the analysis method.

The high-resolution analysis strengths were: spatially explicit results; corridors of multiple least-cost-paths are more robust to variability in initial conditions, input data inaccuracy, and uncertainty in model parameters; the scale of the analysis is consistent with the scale of the wildlife spatial interactions (movement, sensory input, etc.); hi-resolution analysis represents the urban morphology at the scale of urban elements.

The data acquisition/availability and computationally intensive nature of our method were its main limitations. As a direction for future research and to further improve the results, we would recommend: use of automatic tools for data generation (from aerial and satellite imagery); integration of observations into model parameter estimation and definition of initial conditions, especially refining resistance values based on a habitat suitability indexing with habitat features and species occupancy mapping of Haifa urban area at a high resolution.

Manipulation of urban matrix qualities can mitigate the negative impact of urbanization on biodiversity and supplement conservation efforts in reserves. Donnelly and Marzluff (2006) encourage greater abundance of native vegetation species outside reserves by minimizing impervious surfaces and maximizing retention of trees as well as increasing variability of development design pattern. Intermediate landscape heterogeneity together with high-quality matrix and abundant seminatural elements in the landscape, could enhance local biodiversity despite the fact that the landscape is fragmented, or perhaps because of it (Le-Roux, 2010; Tscharntke et al., 2012), given a network that connects these elements and facilitates movement. Preserving connectivity of open spaces is an important step toward biodiversity conservation targets. For medium-sized mammals, connectivity enables movement between habitat patches and thus survival in an urbanized environment.

Planners are increasingly involved in management and preservation of open spaces. Most planning tools for protection of exurban open spaces are on national or regional level, at a very crude resolution, and some are nonstatutory and not binding. Environmental impact assessments in Israel are mandatory only for development plans and master plans. We encourage use of high-resolution impact assessment reports as a prerequisite for master plan preparation. At the planning stage, vegetated open areas can be strategically allocated to preserve connectivity by comparing planning scenarios using connectivity analysis method proposed here. Moreover, a comparison of contribution to connectivity of different open-space types is a promising application of this method.

Urban planning for biodiversity conservation calls for integrated planning efforts to combine an interconnected system of protected nature reserves and seminatural vegetated areas, together with parks and recreational facilities, agricultural and urban land uses. This includes increasing native vegetation cover in urban land-use; supporting and managing the heterogeneous vegetation cover rather than homogenous lawns and manicured gardens; designing parcel boundaries and fences penetrable for the desired species movement (Donnelly and Marzluff, 2006). Improving connectivity between open spaces entails maximizing vegetation in the other land uses as well as maximizing the amount and area of vegetated urban open spaces themselves, and has a potential to improve urbanites quality of life while pursuing the nature conservation purposes.

Urban porosity is a complex phenomenon. It changes with time and varies with urban morphology and across the cityscape. Open spaces in cities comprise complex networks that consist of connected patches of different quality and quantity. Parts of cities remain permeable to movement of mammals and enable communities to persist. Evaluation of urban porosity in terms of movement of mammals and decisions concerning the importance of particular patches and corridors for the sustainability of the network requires fine-resolution analysis and parameters that pertain to particular species.

This paper is part of an effort to address urban open space in a spatially explicit and ecologically based context. Here, we react to the extant planning discourse concerning urban open spaces that are residuals of the spatial expansion of the built environment. The resulting land-cover pattern is frequently evaluated, in terms of its influence on the environment, at a crude spatial resolution only. We claim that, at the low resolution, the open-space pattern disappears. To evaluate the ecological significance of urban open spaces, one has to perform that analysis at the fine resolution of backyards and vegetated areas along the sidewalks, trails, and roads.

Acknowledgements

We are thankful for useful comments to Rüdiger Prasse, Michael Batty, Eyal Herlin, and to Ori Hay. We are also thankful for technical advice to Jérémy Fiegel and Lev Toger. We are grateful to the referees for their time and constructive comments.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: We are thankful for funding to Irwin and Joan Jacobs Graduate School (Technion), to Miriam and Aaron Gutwirth Memorial Fellowship, to Lower Saxony funding for Scientific Cooperation between Lower Saxony and Israel (Braunschweigische Wissenschaftliche Gesellschaft), and to Israel Science Foundation (ISF Grant No. 94951).

Notes

1. Data preparation and initial processing were performed jointly by Marina Toger (Technion) and by Yulia Grinblat and Einat Roth (Tel Aviv University).
2. We used motion-sensor triggered cameras to detect mammal activity in Haifa open spaces. The open spaces were defined as having 75% or more of unsealed surface land-cover. The patches were divided into nine groups by size and distance from Carmel forests boundary. The sampling sites were selected using stratified random approach. In the 2011 sampling series, eight wild mammal species were detected, including Indian crested porcupine. We plan to report our findings in detail elsewhere.

References

Alberti M (2005) The effects of urban patterns on ecosystem function. *International Regional Science Review* 28(2): 168–192. DOI: 10.1177/0160017605275160. Available at: http://irx.sagepub.com/content/28/2/168.short

Alonso W (1964) *Location and Land Use*. Cambridge: Harvard University Press.

Balter N (2010) *The development of the structure of urban open spaces: A demonstration on Haifa's Carmel City*. Haifa: MSc Thesis, Technion Israel Institute of Technology. Available at: http://www.graduate.technion.ac.il/Theses/Abstracts.asp?Id = 24697 (acessed 26 June 2014).

Barshaw D (2012) Rotten Hogs! Web-blog post. *The times of Israel*. http://blogs.timesofisrael.com/rotten-hogs/ (acessed 14 July 2014).

Bastian M, Heymann S and Jacomy M (2009) Gephi: An open source software for exploring and manipulating networks. *ICWSM* 8: 361–362.

Benguigui L, Blumenfeld E and Czamanski D (2006) The dynamics of the Tel-Aviv morphology. *Environment and Planning B* 33(2): 269–284.

Benguigui L and Czamanski D (2004) Simulation analysis of the fractality of cities. *Geographical Analysis* 36(1): 69–84.

Benguigui L, Czamanski D, Marinov M, et al. (2000) When and where is a city fractal? *Environment and Planning B* 27: 507–519.

Bettencourt L and West G (2010) A unified theory of urban living. *Nature* 467(7318): 912–913.

Bolund P and Hunhammar S (1999) Ecosystem services in urban areas. *Ecological economics* 29(2): 293–301.

Broitman D and Czamanski D (2012) Cities in competition, characteristic time and leapfrogging developers. *Environment and Planning B* 39(6): 1005–1118.

Cadenasso ML, Pickett ST and Schwarz K (2007) Spatial heterogeneity in urban ecosystems: Reconceptualizing land-cover and a framework for classification. *Frontiers in Ecology and the Environment* 5(2): 80–88.

Central Bureau of Statistics (2009) *Population Census 2008*. Israel Central Bureau of Statistics. p.134. Available at: http://www.cbs.gov.il/reader/shnaton/templ_shnaton.html?num_tab = st02_16&CYear = 2008

Czamanski D, Benenson I, Malkinson D, et al. (2008) Urban sprawl and ecosystems—Can nature survive? *International Review of Environmental and Resource Economics* 2(4): 321–366.

Czamanski D and Broitman D (2012) Developers' choices under varying characteristic time and competition among municipalities. *Annals of Regional Science* 49(3): 733–743.

Donnelly R and Marzluff JM (2006) Relative importance of habitat quantity, structure, and spatial pattern to birds in urbanizing environments. *Urban Ecosystems* 9(2): 99–117.

ESRI (2012) *ArcGIS Desktop Release 10.1*. Redlands, CA: Environmental Systems Research Institute.

Ewing RH (2008) Characteristics, causes, and effects of sprawl: A literature review. In: *Urban Ecology*, Section V. Springer US, pp. 519–535.

Frenkel A and Ashkenazi M (2008) Measuring urban sprawl: How can we deal with it?. *Environment and Planning B* 35(1): 56–79.

Goddard MA, Dougill AJ and Benton TG (2010) Scaling up from gardens: Biodiversity conservation in urban environments. *Trends in Ecology and Evolution* 25(2): 90–98.

Google maps (2012). Available at: http://www.google.com/maps/place/Haifa,+Israel/ (acessed January 2013).

Gual M and Norgaard R (2010) Bridging ecological and social systems coevolution: A review and proposal. *Ecological Economics* 69(4): 707–771.

Haifa Municipality (2012) *Statistical Yearbook of Haifa*. Available at: http://www1.haifa.muni.il/spru/doc/Fad/haifa_ENG.pdf

Helbing D, Yu W and Rauhut H (2009) Self-organization and emergence in social systems. Modeling the coevolution of social environments and cooperative behavior. *The Journal of Mathematical Sociology* 35(1–3): 177–208.

Hilty JA, Lidicker WZ Jr and Merenlender A (2006) *Corridor Ecology: The Science and Practice of Linking Landscapes for Biodiversity Conservation*. Washington, DC, USA: Island Press.

Hobbs RJ, Higgs ES and Hall C (2013) *Novel Ecosystems: Intervening in the New Ecological World Order*. Oxford, UK: John Wiley and Sons.

HP (2009) Haifa municipality urban plan HP2000. In Hebrew. Available at: http://www1.haifa.muni.il/mitar/chapters/chap2.pdf

Kong F, Yin H, Nakagoshi N, et al. (2010) Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. *Landscape and Urban Planning* 95(1): 16–27.

Le-Roux X (2010) Relationships between agriculture and biodiversity: Key messages from the recent state-of-the-art published in France. In: *Nekudat-Hen Symposium*, Ramat Hanadiv. Available at: http://www.nekudat-hen.org.il/%D7%9E%D7%A7%D7%95%D7%A8/relationships-between-agriculture-biodiversity-key-messages-recent-state-art-published-france

Licoppe A, Prévot C, Heymans M, et al. (2013) *Wild boar/feral pig in (peri-)urban areas. International survey report as an introduction to the workshop Managing wild boar in human-dominated landscapes*. Congress of International Union of Game Biologists IUGB 2013, Brussels, Belgium. Available at: http://www.iugb2013.org/docs/Urban%20wild%20boar%20survey.pdf/ (accessed 20 June 2015).

Maruani T and Amit-Cohen I (2007) Open space planning models: A review of approaches and methods. *Landscape and Urban Planning* 81(1): 1–13.

Matthies S, Kopel D, Rüter S, et al. (2013) Vascular plant species richness patterns in urban environments: Case studies from Hannover. In: Malkinson D, Czamanski D and Benenson I (eds) *Modeling of Land-Use and Ecological Dynamics*. Germany and Haifa, Israel: Springer Berlin Heidelberg, pp. 107–118.

Mills ES (1972) *Studies in the Structure of the Urban Economy*. Baltimore: Johns Hopkins Press.

Morgado P, Toger M, Abrantes P, et al. (2012) A bottom-up approach to modeling habitat connectivity dynamics through networks analysis. In: Curkovic S (ed.) *Authoritative and Leading Edge Content for Environmental Management*. INTECH Open Access Publisher. DOI: 10.5772/45939. Available at: http://www.intechopen.com/books/sustainable-development-authoritative-and-leading-edge-content-for-environmental-management/a-bottom-up-approach-to-modeling-habitat-connectivity-dynamics-through-networks-analysis

Muth RF (1969) *Cities and Housing; the Spatial Pattern of Urban Residential Land-Use*. Cicago, IL, USA: University of Chicago Press.

Naali A (2009) *Olive groves plantation as a sustainable solution to abandoned agricultural land*. PhD Thesis, University of Haifa (in Hebrew). Available at: http://digitool.haifa.ac.il/R/CYXB8LSMEXYPAYSGJAY2VCB3J2H6VDVK55J37DR7GPMDJGX2YV-02353?func=search-simple-go&local_base=GEN01&find_code=WCO&request=Naali%2C%20Adi (accessed 26 March 2015).

Orenstein DE and Hamburg SP (2010) Population and pavement: Population growth and land development in Israel. *Population and Environment* 31(4): 223–254.

Pinto N and Keitt TH (2009) Beyond the least-cost path: Evaluating corridor redundancy using a graph-theoretic approach. *Landscape Ecology* 24(2): 253–266.

Rudnick D, Ryan SJ, Beier P, et al. (2012) The role of landscape connectivity in planning and implementing conservation and restoration priorities. *Issues in Ecology* 16: 1–20.

Saltz D and Alkon PU (1989) On the spatial behaviour of Indian crested porcupines (Hystrix indica). *Journal of Zoology* 217(2): 255–266.

Sawyer SC, Epps CW and Brashares JS (2011) Placing linkages among fragmented habitats: Do least-cost models reflect how animals use landscapes? *Journal of Applied Ecology* 48(3): 668–678.

Sever Z and Mendelssohn H (1991) Spatial movement patterns of porcupines (Hystrix indica). *Mammalia* 55(2): 187–206.

Shoshany M and Goldshleger N (2002) Land-use and population density changes in Israel- 1950 to 1990: Analysis of regional and local trends. *Land-use Policy* 19(2): 123–133.

Spear SF, Balkenhol N, Fortin MJ, et al. (2010) Use of resistance surfaces for landscape genetic studies: Considerations for parameterization and analysis. *Molecular Ecology* 19(17): 3576–3591.

Tardin R (2012) *System of Open Spaces: Concrete Project Strategies for Urban Territories*. Springer US.

Tscharntke T, Tylianakis JM, Rand TA, et al. (2012) Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological Reviews* 87(3): 661–685.

Urban D and Keitt T (2001) Landscape connectivity: A graph-theoretic perspective. *Ecology* 82(5): 1205–1218.

VanDruff LW and Rowse RN (1986) Habitat association of mammals in Syracuse, New York. *Urban Ecology* 9(3): 413–434.

Wilensky U (1999) *NetLogo software*. Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University. Available at: http://ccl.northwestern.edu/netlogo/ (accessed April 2012).

Winder N, McIntosh BS and Jeffrey P (2005) The origin, diagnostic attributes and practical application of co-evolutionary theory. *Ecological Economics* 54(4): 347–361.

Zeller KA, McGarigal K and Whiteley AR (2012) Estimating landscape resistance to movement: A review. *Landscape Ecology* 27(6): 777–797.

Marina Toger is a PhD candidate and research associate at ComplexCity research lab, at the Faculty of Architecture and Town Planning, Technion—Israel Institute of Technology, Israel. Her research comprises application of complexity theory to the study of urban dynamics and planning, spatially explicit models of urban morphology, specifically urban open spaces as an interconnected network.

Dan Malkinson is a landscape ecologist, holding a position of a Senior Lecturer at the Department of Geography and Environmental Studies and at the Golan Research Institute at the University of Haifa. His work entails the study of landscape structure, ecological dynamics, and their interactions with respect to human modifications of these systems.

Itzhak Benenson is a Professor of Geography at the Department of Geography and Human Environment, Tel Aviv University, and Head of Geosimulation and Spatial Analysis laboratory. His research includes study of big urban data, modeling of urban land use and residential dynamics, the impact of local and regional plans, use of public transport and parking in the city and vehicle-pedestrian interactions and road accidents. Itzhak Benenson is an associated editor of Computers Environment and Urban System journal and serves on the editorial board of several journals. He is a member of IGU Commission on Geographical Information Science.

Daniel Czamanski is a Professor of urban economics in the Faculty of Architerctutre and Town Planning at the Technion—Israel Institute of Technology and head of the ComplexCity Research Lab. His research focuses on the spatial dynamics of cities. He serves on the editorial boards of several journals.

Appendix 1: High-resolution connectivity analysis

Definitions

Core area—protected seminatural vegetated open spaces large enough to support viable populations; in Haifa it is the Carmel Forest. Patches connected to the core area (directly or through other patches) comprise the accessible part of the open-space network.

Open spaces—unbuilt open patches with seminatural vegetation as opposed to managed vegetated areas as in parks, backyards, or gardens. These open spaces contain suitable habitat for the mammal species in question, but are too small to support the populations by themselves. These patches cannot serve as permanent habitats and yet they are important for connecting the larger open spaces.

Transit areas consist of several classes defined by resistance that they present to animal movement. They include parks, small streets and roads, backyards, alleys, footways, agriculture, and garbage sites. Movement within the city boundary will eventually entail crossing roads or paved areas, the transit areas with high resistance. Managed vegetated open spaces are irrigated, implement pest control, and often contain planted nonnative species (Alberti, 2005). In this analysis, they are part of the transit land-cover type.

Obstacles are hostile areas e.g. buildings, water, construction sites, walls, and other impassable land-cover types.

Cell costs—landscape resistance to movement values for each cell. In an urban setting, resistance to movement is determined by disturbance from human activities, here based on the land use/land cover of the land patch. A cost value of 0.1/m means that the terrain is 90% permeable (Table 1). The lower the cost value, the higher the permeability of the cell. Hence, we use the concept of the cost of movement; it represents the friction of the resistance to movement present in the landscape. The resistance values are based on species-specific response to different land-cover types.

Connectivity—the ability to provide animal movement between the patches.

Paths—connections between open spaces through the heterogeneous landscape, detected using multiple least-cost-path analyses. For simplicity, we disregarded slopes, so path cost from origin to destination is equal to path cost from destination to origin; thus, here the paths are bidirectional.

Path-cost threshold—a species-specific parameter of the corridor, the max cutoff value C* of path cost. Animals travel a certain distance nightly. Mean nocturnal movement distance through the seminatural open space is the basis of the threshold value. Moving through a seminatural vegetated patch, an animal will cover a certain distance in its nocturnal foraging, and occasionally will travel further to mate. For example, Indian crested porcupine pairs are capable of foraging around the den at 0.7–2.8 km/night (Saltz and Alkon, 1989), whereas males in search of mates can cover up to 8 km/night (Sever and Mendelssohn, 1991) through a hilly terrain. Porcupine pairs occupy permanent home ranges with occasional overlap between siblings, whereas single males are not territorial. Porcupines are highly adaptable species and their home-range size and foraging distance vary with food availability (Sever and Mendelssohn, 1991). To account for the seasonal and gender variability in movement distances, multiple paths are obtained with a range of path-cost values. The travel distance will be shorter through more resistant land-cover type cells. Assuming for instance a threshold distance of 8000 m and a cost of 0.1 (meaning that travel is 10 times harder through a given urban land cover than through seminatural vegetated open space), the maximal cost–distance is equal to 800 m. If another less friendly land use/land cover is 50% more resistant than open space, with the cell cost value of 0.5/m, then max travel distance is 80 m through that land-use/land-cover type.

Corridor detection method

Cost surface preparation.

- Aerial images were manually digitized into vector polygons of 20 land-use/land-cover classes (Table 1).
- Land-use/land-cover polygon layer was rasterized, and each 5 m cell was assigned the cost/resistance value.

Link construction (for each origin–destination pair)

(1) Choose a pair of open-space patches, an origin and a destination.
(2) Run least-cost-path from origin to destination over the resistance surface.
(3) Save the found least-cost-path.
(4) If the path cost of the found least-cost-path is less than cutoff cost value C* then continue.
(5) Else stop, this is the last path for the origin–destination pair.
(6) Construct the new resistance surface with the found least-cost-path "spent" cells values increased by a value of ΔC, other cells values and open-space cells cost values remain the same as before.
(7) Repeat step 4 using the new resistance surface.
(8) Output: The multiple paths with cumulative cost value increasing from least cost to the cutoff value C*. These multiple paths comprise a complex link pattern of the possible choices of routes, the corridor.

Formally, we establish

- every 5×5 landscape cell is assigned a cost of crossing per meter of movement
- species-specific cost threshold C* that an animal may accumulate on the path between two open spaces
- increase in cell cost ΔC for cells that already participated in a previously found path, a model parameter

Link construction:

- Then we search for the k paths with cost below the C* threshold.

To implement the procedure, we developed a tool that exploits the raster least-cost-path algorithm. We applied the procedure to the areas that include both patches and sufficient margins around them. The approach was applied to every pair of patches P_1 and P_2 at an aerial distance below C*. Let the cost of the shortest path between P_1 and P_2 be C_1:

- If $C_1 > C^*$, then P_1 and P_2 are not connected, otherwise.
- Increase the cost of every cell included into C_1 by ΔC, apply the algorithm again and obtain the second least-cost path C_2 (ΔC is the incremental increase in cost).
- Repeat and obtain all least-cost paths C_k satisfying $C_k \leq C^*$.
- Establish the movement corridor by combining the cells of all paths C_k between P_1 and P_2.

The lower is the difference in cost of passage ΔC, the better will be the representation of the corridor. At the same time, the number of paths found with path cost lower than C* will increase with increasing overlap between the paths. The choice of ΔC is thus a compromise between the precision of the corridor representation and computer performance. ΔC should be expressed in units of the cell costs and, thus, depends on the way the costs are assigned. For very low ΔC, paths overlap. When ΔC is increased—additional distinct paths are found. With a very large ΔC, paths are completely foreign and certain branching paths are lost. Optimal ΔC is when most part of the paths differs but not the whole path. Varying this parameter alters the amount of redundant paths found. After experimenting with different values, we chose $\Delta C = 0.01$ as it gave many redundant paths without them being too similar. If totally nonoverlapping paths are needed—value of cells of previous paths increased by infinity.

Next, postfiltering of the found paths is applied to the paths. After all paths between a pair of patches are found, some of the paths should be filtered out based on the local conditions. For instance, a porcupine may not cross a road 80 m wide, even though the total cost of crossing it is within the maximum cost value. At the same time, it is capable of crossing several roads 10 m wide each. This is assuming that wide roads typically have more traffic than narrow ones, are lit during the nights, are noisier, and are characterized by longer gaps without shelter. The additional filtering leads to the final selection of paths between the given origin–destination pair.