

# Landscape patterns of development under two alternative scenarios: Implications for conservation



David Troupin <sup>a,\*</sup>, Yohay Carmel <sup>b</sup>

<sup>a</sup> Faculty of Architecture and Town Planning, Technion—Israel Institute of Technology, Haifa 32000, Israel

<sup>b</sup> Faculty of Civil and Environmental Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel

## ARTICLE INFO

### Article history:

Received 29 December 2014

Received in revised form 16 January 2016

Accepted 7 February 2016

### Keywords:

Urbanization

Urban development

Urban sprawl

Land-cover simulation

Urban-growth management

Scenarios

## ABSTRACT

The spatial pattern of urban development has important ecological and conservation implications. Urban sprawl, characterized by scattered and low-density urban development, is commonly criticized for its negative ecological impact. In response, growth management policies have been proposed in order to promote compact development, which is generally considered more favorable from an ecological perspective. Spatial simulations of land cover change are useful for comparing urban development scenarios and their potential effects. One aspect that has not received much attention is how the rate of development may affect differences between compact development and urban sprawl in terms of their potential impact to biodiversity conservation at the landscape scale. Our goal in this study was to compare the spatial pattern and landscape-scale conservation and ecological implications of sprawling development (expected under unregulated development) versus compact development (promoted by growth management policies) at different development rates. We focused on Israel's Mediterranean region—a region characterized by high human population density and heterogeneous land cover. Using a cellular automata model, DINAMICA-EGO, we calibrated and validated an urban development model for the period between 1998 and 2007. Using this period as a reference, we simulated two scenarios 20 years into the future: unregulated (resulting in a more sprawling development pattern) versus regulated development (resulting in a more compact development pattern). For each scenario we analyzed a range of development rates, and compared built-up area patterns, and several landscape-level attributes of natural habitats, conservation priority areas, and protected areas. We found that at development rates comparable to those observed during 1998–2007, there was no major difference between the two scenarios. At higher development rates, some differences between the scenarios emerged: natural core areas were more fragmented and smaller in their extent, and a higher proportion of conservation priority areas were expected to undergo development in the unregulated scenario. Overall, the regulated scenario was more favorable for conservation. Since the regulated and unregulated scenarios exhibited only minor differences in lower development rates, modifications to policy measures included in the regulated scenario should be considered in order improve its effectiveness.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

Urban development involves the conversion of open land into built-up land that serves various human needs (e.g., residential, industrial, and infrastructure). Urbanization constitutes an extreme form of land-use alteration and is generally considered to have significant detrimental effects on the environment and ecosystems (McDonald et al., 2008). During the 20th century, urbanization lev-

els throughout the world increased dramatically (Angel et al., 2005; Grimm et al., 2008; Seto et al., 2011). Widespread development of urban areas is projected to continue in the 21st century, particularly in developing countries (Cohen, 2006; Montgomery, 2008).

The ecological consequences of urbanization are a major concern for conservation scientists and planners. Much research has been dedicated to mapping the extent and patterns of urban development (Angel et al., 2012; Frenkel and Orenstein, 2012; Seto et al., 2011) and quantifying its ecological impacts (Chace and Walsh, 2006; Chamberlain et al., 2009; Pautasso et al., 2011). Urban sprawl, characterized by widespread low-density urban development over increasingly larger areas of land, has been the subject of intense criticism and debate (Brueckner, 2000; Ewing, 2008; Glaeser and

\* Corresponding author.

E-mail addresses: [davidtroupin@gmail.com](mailto:davidtroupin@gmail.com) (D. Troupin), [\(Y. Carmel\)](mailto:yohay@technion.ac.il).

Kahn, 2003; Gordon and Richardson, 1997). Urban sprawl can be defined and quantified in various ways (Frenkel and Orenstein, 2011). The use of the term urban sprawl in our study refers to a spatial pattern of urban development characterized by noncontiguous leapfrog development, scattered and/or low-density development (Frenkel and Orenstein, 2012; Orenstein et al., 2014). An important argument against urban sprawl concerns its potentially negative environmental impact (European Environmental Agency, 2006; Ewing, 2008), including for example, the fragmentation and loss of habitats (Irwin and Bockstael, 2007; Radeloff et al., 2005; Robinson et al., 2005) caused by scattered and low-density development (Frenkel, 2004a; Hasse and Lathrop, 2003).

To address concerns over the impact of urban sprawl, urban growth management policies and planning measures have been proposed and implemented in many cities and countries, in order to control the patterns, extent, and intensity of urban development (Ewing, 1997; Frenkel and Orenstein, 2012; Razin and Rosentraub, 2000). The objective of many of these policies has been to encourage urban development that is spatially compact. Compactness in the context of our study refers to development characterized by higher densities of population and residential units over smaller areas, and increased spatial aggregation and clustering of built-up areas. Tools and policies that promote compact development include: different types of land-use zoning, definition of urban growth boundaries, and land purchasing by governments (Frenkel, 2004b). From an ecological perspective, compact development is generally considered more favorable: larger areas of natural and agricultural habitats are preserved (Couch and Karecha, 2006; Frenkel and Orenstein, 2012; Robinson et al., 2005) and edge effects are reduced (Ries et al., 2004; Ikin et al., 2014). For example, Sushinsky et al. (2013) found that compact development was more favorable for bird species in terms of local extinctions and distribution reductions, and Gagné and Fahrig (2010) concluded that compact development minimized human impact on forest breeding birds based on their abundance.

However, there is no consensus regarding the negative ecological consequences of sprawling urban development (Czamanski et al., 2008; Lin and Fuller, 2013) or the efficacy of urban growth management policies in controlling urban form and development patterns (Alfasi et al., 2012; Frenkel and Orenstein, 2012; Lin and Fuller, 2013). Firstly, Some have argued that low-density development is not necessarily ecologically detrimental and that it may in fact support biodiversity (Czamanski et al., 2008; see Lin and Fuller, 2013). The idea is that, in contrast to high-density intensive development, in areas with low-density development ecological consequences are less severe at a local scale and larger areas of urban green space (e.g., backyards, parks, avenues, greenways) can be retained. Such areas may even support and maintain high species diversity (Sandström et al., 2006), provide essential habitats (Bryant, 2006; Mo et al., 2000), and serve as buffers between areas of intensive agriculture and dense urbanization (Czamanski et al., 2008). Secondly, since the effectiveness of policies depends on multiple social, historical, economic and political factors (Frenkel and Orenstein, 2012; Lin and Fuller, 2013), only a few studies (reviewed by Frenkel and Orenstein, 2012) have empirically assessed the effectiveness of growth management policies in preserving undeveloped land and open space, and these studies have provided mixed evidence (Alfasi et al., 2012; Dallimer et al., 2011; Frenkel and Orenstein, 2012).

Israel's Mediterranean region is characterized by high human population density and high demand for development of land (Frenkel and Orenstein, 2012; Orenstein and Hamburg, 2010; Schaffer and Levin, 2014). A recent report by the Israel Society for Nature Protection (Ben David and Avni, 2013) listed dozens of local-scale cases in which planned development poses threats to remaining natural and semi-natural habitats in the region. In

addition to the concern over the loss of natural habitats, conservation concerns that are relevant to this region include: (a) insufficient coverage by protected areas—protected areas in the region do not provide adequate protection and representation for most habitat types (Levin et al., 2007; Weil and Levin, 2015) and for several groups of species that have been examined, including breeding birds (Troupin and Carmel, 2014) and endangered vertebrates (Dolev and Carmel, 2009); (b) reduced spatial connectivity between natural and agricultural patches (Achiron-Frumkin, 2011; Levin et al., 2007); and (c) edge effects caused by settlements – e.g., changes in community structure resulting from increased development and the proximity of natural habitats to settlements – such differences between woodlands that are close to settlements and woodlands that are more distant from settlements were found for mammals, birds and butterflies (Berg et al., 2015).

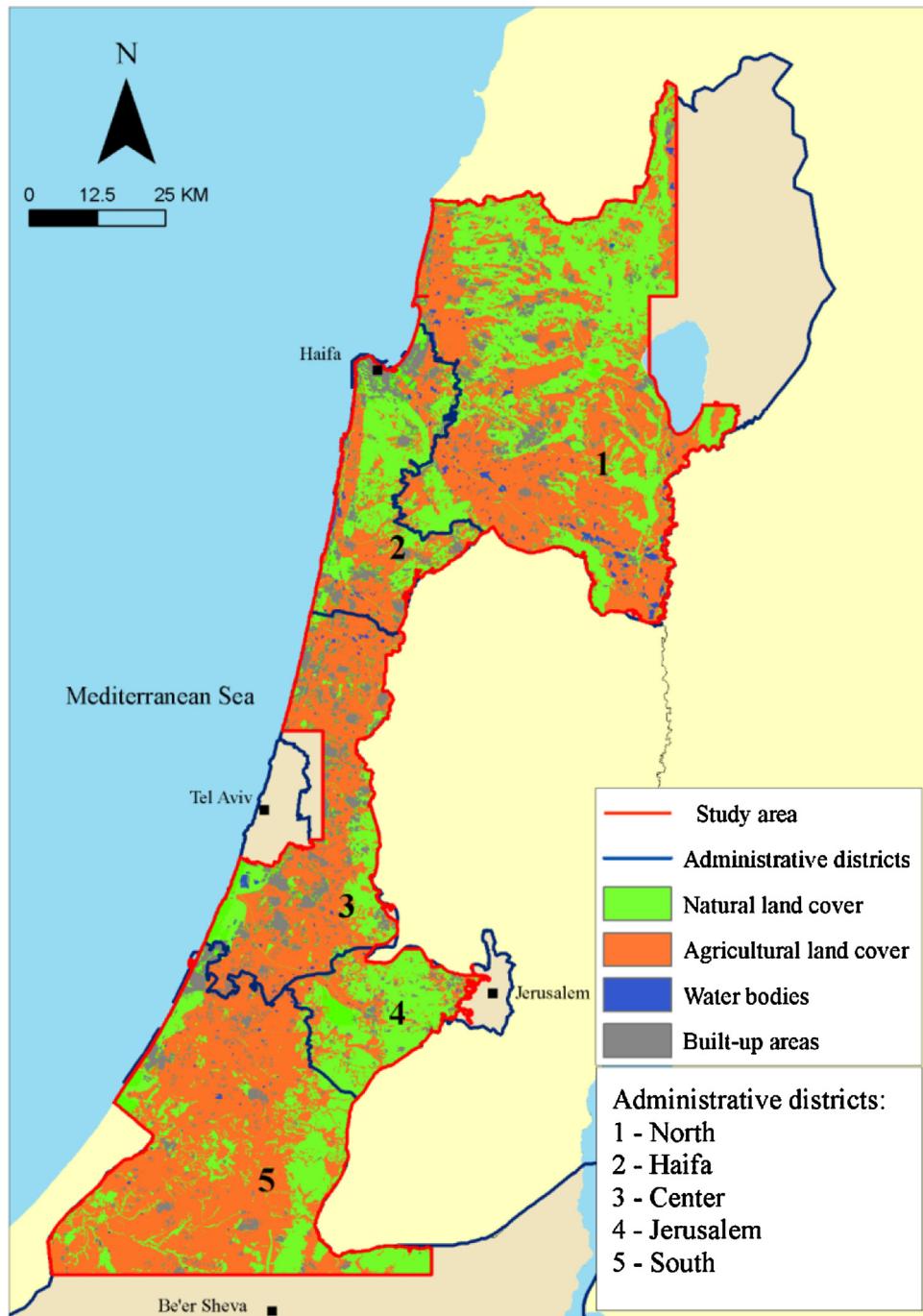
In summary, the spatial pattern of urban development can have important ecological and conservation implications. One of the main questions that current research addresses is which urban development pattern is more favorable in terms of ecological and biodiversity conservation (where should urban development take place and what should its spatial form be). One aspect that has not received much attention is how the rate of development affects the differences between compact development and urban sprawl in terms of spatial pattern and the potential implications to biodiversity conservation at the landscape scale.

Our goal in this study was to compare the spatial pattern and landscape-scale conservation and ecological implications of sprawling development (which is expected under unplanned and unregulated development) versus compact development (which is promoted by growth management policies) at different development rates. We examined this question for Israel's Mediterranean region. We used a land cover simulation model to construct and compare two scenarios of urban development 20 years into the future: (1) an unregulated development scenario, representing a situation in which the guidelines of the national-level plan are ignored, altered, or unenforced—resulting in urban sprawl; (2) a regulated development scenario which is based on the policy outlined in the national-level plan (e.g., development in adjacency to existing built-up areas)—resulting in a more compact spatial form. We simulated both scenarios over a range of increasing development rates in order to assess how varying development rates affected the differences between the scenarios, specifically the effectiveness of the regulated development scenario, and account for uncertainties in projected new development. We analyze and discuss the resultant spatial patterns of built-up areas simulated under each scenario and their potential implications for conservation at the landscape scale.

## 2. Methods

### 2.1. Study area

The study area, Israel's Mediterranean region, lies between latitudes 30° and 33° and encompasses an area of approximately 7,000 km<sup>2</sup> (Fig. 1). In this study we used a land-cover map that was produced by overlaying the most recent land-cover data from several sources (Table 1). Troupin and Carmel (2014) used this map to define the preferred habitats of the breeding birds in Israel's Mediterranean region and examine different strategies for selecting conservation priority areas for this group of species. The land cover (Fig. 1; Table 2) consists mainly of agricultural land (crops and plantations, approximately 53%), natural habitats (primarily Mediterranean type vegetation formations, approximately 37%) and built-up areas (primarily human settlements, approximately 10%).



**Fig. 1.** The aggregated land cover classes in the study area and borders of administrative districts.

**Table 1**

Land cover data sources. All layers were provided as vector layers and converted into raster format at a resolution of 50 m.

Data	Source	Year
Natural vegetation	Israel Nature and Parks Authority	1995
Agricultural plantations and croplands	Israel Central Bureau of Statistics	2002
Built-up area	Israel Ministry of Interior	2007
Running streams and water bodies	The Hebrew University GIS center	2008
Vegetation in Jewish National Fund managed areas	Jewish National Fund	2009

The land cover map included twelve land cover classes (Table 2) and permitted the distinction between natural (or semi-natural) vegetation/land cover and agricultural vegetation: For the purposes

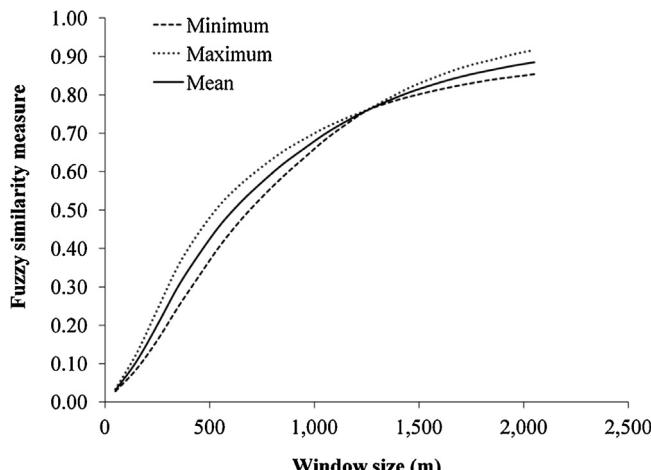
of our study we aggregated classes 1–8 and 9–10 into natural and agricultural land cover, respectively (Table 2; Fig. 1).

The National Outline Plan 35 (NOP 35), which has been in effect since 2005, includes a growth management policy involving a

**Table 2**

Land cover classes in the study area.

No.	Class	% of study region	Aggregated class
1	Herbaceous vegetation	2.13	Natural
2	Sparse shrubs	3.06	Natural
3	Dense shrubs	2.39	Natural
4	Sparse trees	5.39	Natural
5	Dense trees	7.42	Natural
6	Planted forest	9.25	Natural
7	Other natural vegetation	2.76	Natural
8	Riparian vegetation	0.52	Natural
9	Agricultural plantations (orchards, groves, etc.)	14.60	Agricultural
10	Croplands	38.00	Agricultural
11	Water bodies (fish ponds, water reservoirs, etc.)	1.08	Water bodies
12	Built-up	13.40	Built-up
<b>Total area (km<sup>2</sup>)</b>		<b>7,804</b>	

**Fig. 2.** Multiple window fuzzy similarity measures obtained from the comparison between the observed changes and simulated changes between 2003 and 2007.

number of development restrictions, such as requiring new urban development to take place in adjacency to existing urban built-up areas, concentrating development in defined areas, intensifying existing built-up areas, and enforcing minimal density levels in new areas of development (Assif and Shachar, 2005; Frenkel, 2004a). The study area includes five regional administrative districts: North, South, Center, Haifa, and Jerusalem; Fig. 1. We excluded the Tel Aviv administrative district and the city of Jerusalem from the study area, since land cover data (the distribution of agricultural versus natural land cover; see Table 1) for these areas were incomplete and they are both mostly built-up already. Each district has a District Outline Plan, which is a comprehensive plan specifying long-term planning policies and allocating planning rights, in accordance with NOP 35. Each plan includes a zoning map that designates the planned land-uses.

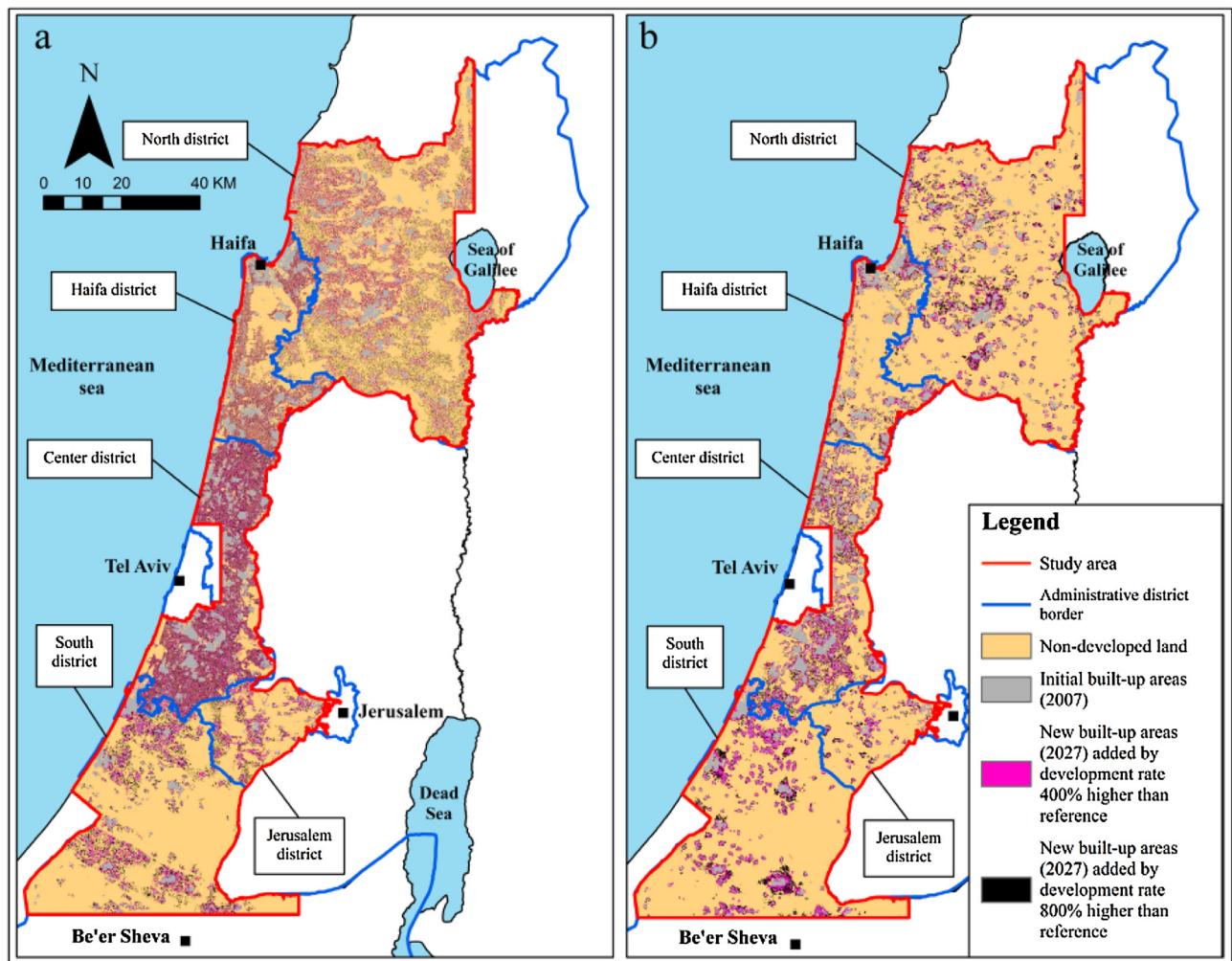
## 2.2. Urban development simulation framework

As part of the preparation and assessment of NOP 35, the Israeli Ministry of Interior mapped built-up areas at a national scale using aerial photos in three time points: 1998, 2003, and 2007. For each of these years built-up area was digitized using a similar methodology. These data provide an opportunity to assess urban development over time. Based on these maps (provided by the Israeli Ministry of Interior) we calibrated and validated an urban development model. We used this model to simulate a reference scenario (extrapolating observed trends into the future), which served as a reference for the two scenarios discussed here. We performed the simulations using DINAMICA-EGO version 2.4.1

(Soares-Filho et al., 2002) which is software that serves as a platform for spatial environmental modeling. One of its main uses is modeling land-use and cover change over time and space using a cellular automata simulation model. Cell size in our model was 50 m and its inputs included: (a) an initial land cover map—we used the built-up data from 1998, 2003 and 2007 for model calibration and validation, and the 2007 map (the most recent available year) as the starting point for simulations into the future; (b) transition matrices containing the probabilities of each possible change between land cover types. In our case this included a single transition type—from non-developed land into built-up/developed land. We calculated the annual transition rate for each administrative district separately using cross-tabulation between the maps from 1998, 2003 and 2007 (using an operation available in DINAMICA EGO); (c) a map of spatial transition probability—this is a map that shows the transition probability for each cell. We produced this map using the Weights of Evidence method which is available in DINAMICA EGO (Bonham-Carter, 1994; Soares-Filho et al., 2010). The Weights of Evidence is a Bayesian method and it has the advantage of not being constrained by the statistical assumptions of parametric tests such as linear regression or logistic regression which are often violated by spatial data (Nti and Sallis, 2014; Soares-Filho et al., 2010). As input variables for the Weights of Evidence method we used the following driving factors which were chosen based on the findings of previous studies in the study area: (1) distance to existing built-up areas; (2) average sub-district (an administrative division within districts) population growth in the five years preceding the simulation's initial year; (3) distance from major roads and highways; (4) population density in sub-districts in the simulation's initial year; (5) land-use; (6) distance from major running streams; and (7) protection status. In Appendix A we provide details on the data sources for the input variables we used and the results of this analysis. Detailed descriptions of the Weights of Evidence method and its implementation in DINAMICA EGO for producing spatial probability maps can be found in Soares-Filho et al. (2010, 2009) and Ximenes et al. (2011); and (d) the size distribution of new built-up patches and expansion areas (by controlling the mean, variance and shape—isometry), and the relative proportions of new built-up patch generation vs. existing patch expansion (the patcher/expander parameter)—we calculated these parameters for the data from 1998, 2003, and 2007 and calibrated them iteratively. The output of the simulation model is a land cover map. We ran the model for 20 time-steps (years) and used the final simulated land cover map for further analyses.

## 2.3. Model validation

We assessed model performance by running the simulation for the period of 2003–2007, using the same parameters obtained in the calibration (1998–2003). We compared the simulated and



**Fig. 3.** Developed areas in the (a) unregulated and (b) regulated scenarios after 20 years. Built-up areas added in the simulation with development rate 800% higher than the reference rate include also those added in the simulation with development rate 400% higher than reference rate.

observed maps using the “reciprocal fuzzy comparison method” (Almeida et al., 2008; Soares-Filho et al., 2013, 2009). Rather than compare the simulated and observed maps on a cell-by-cell basis this method compares similarity at the neighborhood context (a defined area around a central cell). This is a useful approach for comparing the similarity of spatial patterns (Soares-Filho et al., 2013) and therefore is appropriate for our case-study since we focused on comparing the effects of urban development spatial patterns.

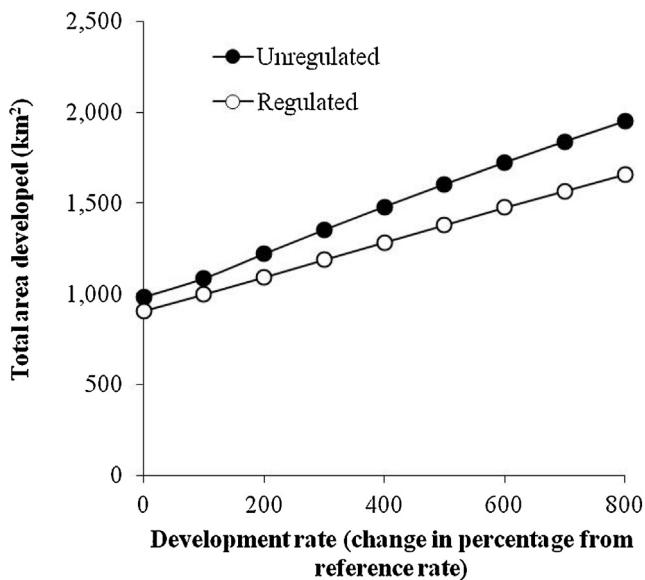
The method involves the calculation of two maps of changes: (1) between the initial map and the simulated map at the end of the studied time period; and (2) between the initial map and the observed map at the end of the studied time period. Then, over a range of increasing window sizes (e.g., 1 × 1 cell, 3 × 3 cells, etc.), two similarity measures are calculated—the match (spatial fit) of map 1 to map 2, and vice versa (a value of 1 is assigned to a matching cell within the given window). This two-way comparison yields two measures of overall similarity (spatial fit)—minimum and maximum. The similarity index ranges from 0 (total dissimilarity) to 1 (total similarity). The overall similarity can then be obtained by averaging the two-way similarity values for all map cells (Fig. 2). Detailed explanations of this method can be found elsewhere (Almeida et al., 2008; Maeda et al., 2011; Ximenes et al., 2011).

At the single cell resolution (50 m) the similarity between the observed and simulated maps was relatively low compared to

larger window sizes. As window size increased, the average similarity between the 2007 observed and simulated maps increased. This pattern is consistent with the findings of other studies that have used this method (e.g., De Rezende et al., 2015; Maeda et al., 2011; Nti and Sallis, 2014; Salonen et al., 2014). We found that the similarity between the maps of observed and simulated changes exceeded 50% at a resolution of 650 m (12 × 12-cell window size) and reached > 80% at a resolution of 2,050 m (22 × 22-cell window size; Fig. 2). While determining acceptable performance of spatial models is specific to the case-study (Hagen-Zanker and Lajoie, 2008; Soares-Filho et al., 2013), the similarity values are comparable to those found in several studies (Maeda et al., 2011; Salonen et al., 2014).

#### 2.4. Simulation of future scenarios

We constructed two urban development scenarios. Both scenarios are based on the work of Frenkel (2004a, b) who developed a land consumption model that served to forecast land needs for development and examine alternative land-use scenarios during the preparation of NOP 35 and Israel 2020—A Master Plan for Israel in the 21st Century (Mazor, 1993). The first scenario, unregulated development, corresponds to Frenkel's continuation of current trends scenario (Frenkel, 2004b) and also draws from the findings of Alfasi et al. (2012), who compared planned and actual land-uses within the Center district of the study area. The second scenario,



**Fig. 4.** Total area developed after 20 years in each simulation as a function of the change in development rate relative to the reference rate.

regulated development, corresponds to Frenkel's growth management policy implementation scenario. We describe both scenarios below. Their main differences are in the overall development rate, the relative proportion of development in the different administrative districts, and the resulting spatial pattern of built-up land.

#### (a) Unregulated development

This scenario corresponds to a situation in which local policy and market forces dictate the spatial development, resulting in continued urban sprawl (Frenkel, 2004a, b). This essentially means that the development guidelines outlined by NOP 35 will not be followed. Alfasi et al. (2012) recently argued that this is in fact the case, at least in the Center district, where they found large gaps between land-uses designated by statutory plans and actual land-uses, and showed that development was not restricted by land-use designations of comprehensive district outline plans: In their words: “*The actual case-by-case development gradually erodes land-uses originally allocated for farmland and for nature and scenic landscape, turning them into built areas.*”

Compared to the regulated development scenario, in this scenario development rates are higher in the central region (Haifa, Jerusalem and the Center districts) than in the peripheral regions (North and South districts) and the overall development rate is also higher. While our simulations did not refer to the number or density of residential units it is assumed that in general development in this scenario consisted of a lower residential unit density per a given area compared to the regulated development scenario. Hereinafter this scenario is referred to as the “unregulated scenario”.

In order to simulate this scenario, we made the following changes to the reference scenario parameters (Appendix B): (1) increased the patcher/expander ratios in each district by 50% in order to generate a larger number of new built-up patches (for example, the value was set at 0.6 for the South district, indicating that 60% of development would result in the formation of new built-up patches and 40% of the development would occur adjacently to existing built-up areas, i.e. infill or outward expansion); (2) increased transition probabilities by 25% so that the relative proportion of development in the different districts remained identical to the reference scenario but with increased development rates; (3) decreased mean size of built-up patches by 100% in order to produce a pattern of smaller and more scattered built-up patches; and (4) set the weights of both agricultural and natural land uses in

the spatial probability map to zero in order to reflect a situation in which development is not influenced by current or designated land-use.

#### (b) Regulated development

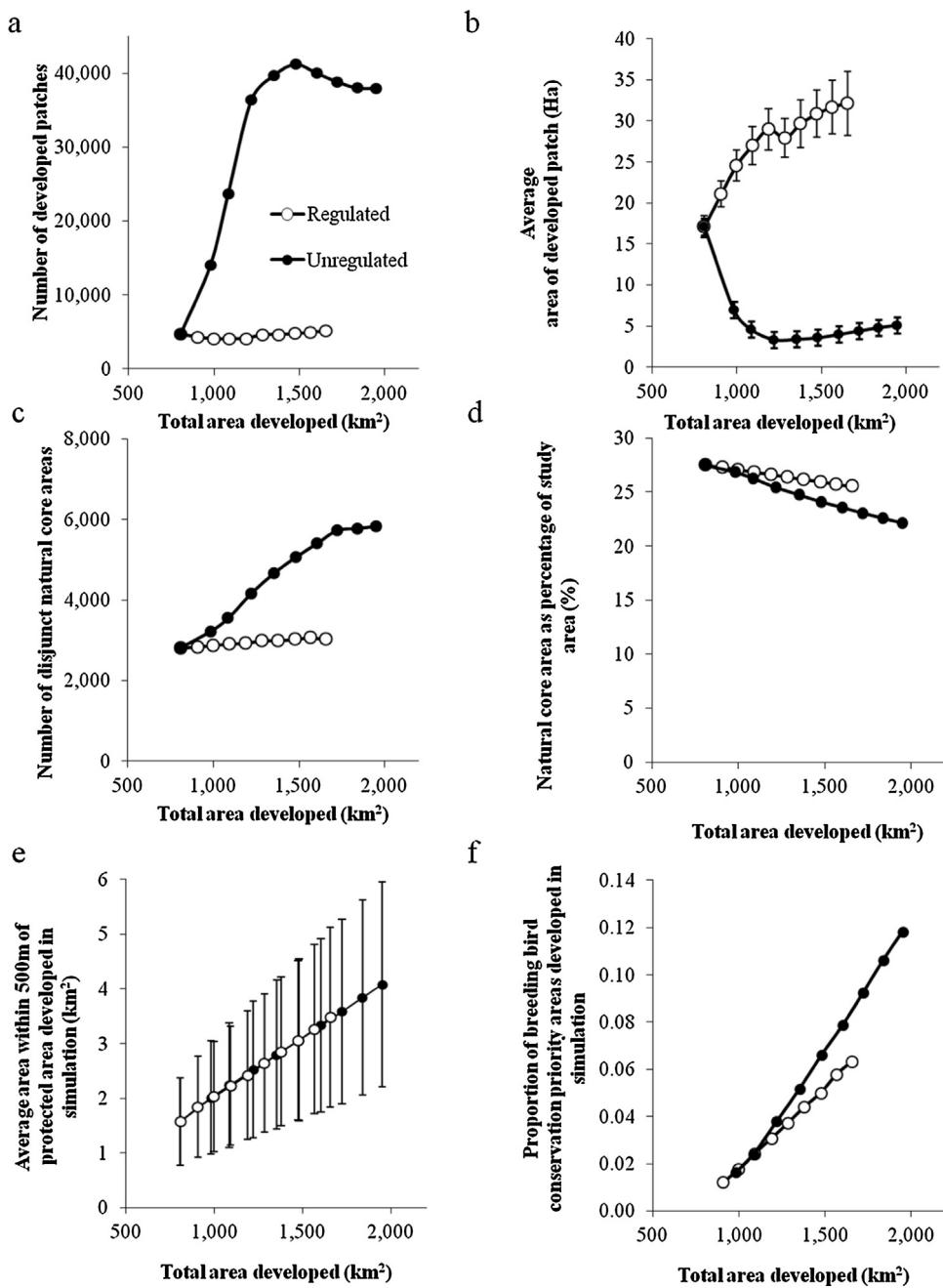
This scenario represents a growth management policy and assumes that future development and land-uses will be determined by the policies suggested in NOP 35 (Frenkel, 2004a). According to Frenkel (2004b): “*This policy was manifested by normative goals for population spatial distribution. In order to generate efficient differential use of land in the various areas, binding development restrictions were set in the national plans. These restrictions included, among others, the obligation to attach any new urban development to an existing urban built-up area; the concentration of development in defined areas; a minimum urban-density requirement in the new built-up areas, as well as the intensification of the old built-up areas*”. The term “concentrated development” was used to describe this scenario (Frenkel and Orenstein, 2012; Frenkel, 2004a) since at the regional scale it promotes development and population growth in the peripheral regions (North and South districts) while at the local scale it aims to intensify existing built-up areas (by situating new development adjacent to existing built-up areas, and imposing minimal size of built-up areas and densities). Hereinafter this scenario is referred to as the “regulated scenario”.

In order to simulate this scenario, we applied the following changes to the reference scenario parameters (Appendix B): (1) decreased the patcher/expander ratio by 50% in order to generate a smaller number of new built-up patches (for example, the assigned value of 0.2 in the South district means that 20% of new development will occur in newly formed patches while 80% of new development will be adjacent to existing built-up areas—either infill or outward expansion of existing built-up patches); (2) changed the transition probabilities in each district in order to reflect a situation in which the development in each district is guided by NOP 35—this results in changes in the relative proportion of development in each district—higher development rates in the North and South districts and lower development rates in the central districts (Frenkel, 2004a); (3) increased the mean size of built-up patches by 150% in order to increase the size of built-up patches; (4) replaced the land-use map of the initial year with the map of designated land-use according to district outline plans; and (5) set negative weights ( $W^+ = -2.0$ ) for agricultural and natural land cover, and positive higher weights for areas designated for development ( $W^+ = 2.0$ ). This was done in order to reflect a situation whereby land-use zoning is imposed and receives greater weight.

The parameters used for the reference scenario simulation and for the two urban development scenarios are found in Appendix B. For each scenario we performed a set of simulations, by progressively increasing the transition probabilities (development rate) by 100% each time, up to values which were 800% higher than those in the simulations with the reference development rates. Thus, each scenario was modeled over a range of nine development rates. We conducted one simulation for each development rate. Hereinafter the term “scenario” refers to the set of nine simulations conducted for each scenario, and the term “simulation” is used to refer to a specific development rate in a given scenario.

#### 2.5. Analyses of scenarios

We calculated the following landscape metrics over the entire study area for each simulation in each scenario: (1) number of built-up patches; (2) average area of built-up patches; (3) number of disjunct core natural areas; (4) total natural core area; (5) average built-up area within a 500 m radius of protected areas; and (6) proportion of breeding bird conservation priority areas that were expected to undergo development in each simulation. We chose



**Fig. 5.** (a) number of developed patches, (b) average area of developed patch, (c) number of disjunct natural core areas, (d) natural core area as percentage of study area, (e) average area developed within 500 m of protected area in simulations and (f) proportion of breeding bird conservation priority areas developed in simulations, as a function of the total area developed after 20 years in the unregulated (filled circles) and regulated (open circles) scenarios.

metrics 1–4 since they have been found to be robust and consistent indicators of urban sprawl in the study area (Orenstein et al., 2014) and calculated them using FRAGSTATS (McGarigal et al., 2002). We calculated metrics 1 and 2 using the maps of built-up area produced in each simulation. For the calculation of ‘natural core areas’ (metrics 3 and 4) we included the classes of natural land cover (classes 1–8 in Table 2) which were then buffered inwards by 50 m.

Metrics 5 and 6 and provide further ecological and conservation context. Protected areas for calculation of metric 6 included nature reserves and national parks, as well as forests, managed by the Israel Nature and Parks Authority and the Jewish National Fund’s Forest Authority, respectively. Both organizations provided us with maps of the areas under their management (as of 2009). These layers were provided as vector layers and converted into raster format

at a resolution of 50 m. As conservation priority areas for breeding birds for metric 6 we used the map of natural vegetation conservation priority areas which was produced by Troupin and Carmel (2014) in an analysis of the habitat distributions of 87 breeding bird species using the conservation planning software MARXAN (Ball et al., 2009).

### 3. Results

#### 3.1. Built-up areas under future scenarios

The unregulated scenario resulted in larger areas of built-up land (particularly in the central region of the study area; Fig. 3). For example, assuming the rate of new development remains com-

parable to that of the reference period (between 1998 and 2007), the total area of built-up land in the study area in 2027 ( $t=20$  years) was expected to be 980 km<sup>2</sup> and 906 km<sup>2</sup> for the unregulated and regulated scenarios, respectively. Fig. 3 shows the total area developed in the study area in both scenarios after 20 years for two of the simulated development rates (400% and 800% higher than the reference).

Fig. 4 shows the total area developed in each simulation as a function of the change in development rate relative to the reference rate. This facilitates the comparison of the scenarios with respect to absolute values of developed area rather than relative change in development rate—in Fig. 5 we plot the metrics used to compare the scenarios as a function of the total area developed in each scenario.

The unregulated scenario resulted in a greater number of built-up patches. With increasing rates of development, the number of built-up patches increased more rapidly in the unregulated scenario set than in the regulated scenario (Fig. 5a). The average built-up patch area was consistently smaller in the unregulated scenario (Fig. 5b).

### 3.2. Natural habitats under future scenarios

With increasing rates of development, total natural core area decreased more rapidly in the unregulated scenario (Fig. 5c). Under the unregulated scenario, the number of disjunct natural core areas increased more rapidly with increasing development rates than in the regulated scenario (Fig. 5d), indicating increased fragmentation of natural habitats.

### 3.3. Protected areas and conservation priority areas under future scenarios

In both scenarios the average amount of built-up areas within a 500 m radius of protected areas changed at a similar rate with increasing development rates (Fig. 5e). Under lower development rates, the proportion of breeding bird conservation priority areas (based on Troupin and Carmel, 2014) that were expected to undergo development was similar and relatively small in both scenarios (approximately 1%). However, as the development rate increased, the proportion of breeding bird conservation priority areas expected to undergo development increased more rapidly in the unregulated scenario (Fig. 5f).

## 4. Discussion

Our analysis of a range of development rates revealed that the regulated development scenario (representing a growth management policy) was relatively ineffective when development rates were relatively low. For development rates comparable with those observed in the study area between 1998 and 2007, the regulated and unregulated scenarios exhibited only minor differences in the landscape-scale conservation factors we examined. At increasing development rates, some differences between the two scenarios became apparent: (1) the loss and fragmentation of natural habitats (indicated by the number of disjunct natural core areas) was more pronounced in the unregulated scenario (Fig. 5c and d); (2) the proportion of breeding bird conservation priority areas that were transformed into built-up areas in simulations (and thus can be considered as threatened by development) increased more rapidly in the unregulated scenario (Fig. 5e). These differences suggest that the regulated scenario, which includes the implementation of growth management measures, was more beneficial for conservation of natural areas at the landscape-scale. The main limitation of the regulated development scenario was its relative ineffectiveness in lower development rates. Below we discuss these and other

aspects in further detail and in the context of the available literature.

### 4.1. Urban development under future scenarios

Based on our simulations, at least 1–2% of the study area is expected to undergo development by 2027 (compared to the extent of built-up area in 2007, the year with the most recent data on built-up areas). These values, and the resulting difference between the regulated and unregulated development scenarios are smaller than other estimates: An earlier study (Frenkel, 2004a) estimated that between 1995 and 2020, the area of new built-up land would range between 677 km<sup>2</sup> and 822 km<sup>2</sup>, depending on the scenario. In our simulations, these development rates correspond to increases of 350% and 600% compared to the reference development rate, in the unregulated and regulated scenarios, respectively. Possible explanations for the differences between our results and these estimates could be differences in the modeling approach and data period used for constructing the model. Firstly, while our simulations are spatially explicit and rely on the observed pattern and rate of development, Frenkel's (2004a) model was not spatially explicit and relied on a statistical model that included different input variables such as population growth, population preferences for location and housing type, expected change in standard of living and changes in household size and other policy variables which were implicit in our simulation. Secondly, we used more recent data (1998–2007) than that used in Frenkel's study (primarily data up to 1995). Indeed, analyses conducted as part of the monitoring of NOP 35 (Cohen et al., 2010) indicate that the period between 1998 and 2007 was characterized by lower development rates than those projected during the preparation of the plan. However, these relatively low rates might not persist or be maintained in the future. In fact, available data on construction area indicates that the average area constructed annually between 2008 and 2014 was higher than the average area constructed annually between 2003 and 2007 (Central Bureau of Statistics of Israel, 2015; Appendix C). Thus, while our reference estimates are on the lower end, analyzing a range of development rates enabled us to account precisely for this uncertainty in future development rates.

Compared with the regulated scenario, the unregulated scenario resulted in an increased amount of built-up areas and larger numbers of built-up patches. In the unregulated scenario, in simulations with higher development rates (those in which development rates were 500% or higher than the reference rate), the number of built-up patches decreased slightly and remained relatively constant. This is probably because development in this scenario occurred primarily in the Center district, and as non-developed land was depleted, built-up patches coalesced (see for example Gustafson, 1998; Shi et al., 2012). As noted in Section 2.4, the unregulated scenario concentrated new development primarily in the Center district since one of its characteristics is urban sprawl around main metropolitan areas (Frenkel, 2004a).

### 4.2. Potential ecological effects of urban development

The ecological effects that are most relevant to the discussion of our study are those related to the conversion of natural habitats and the edge effects caused by large number of built-up patches and the increased proximity between built-up areas and natural ecosystems. These occurred in both scenarios, but to a greater extent in the unregulated scenario. Given the increased fragmentation and loss of natural habitat in the unregulated scenario, it is likely to expect that it would have a greater negative impact on natural ecosystems. Examples of ecological effects that are likely to be more severe under the unregulated scenario include: (a) loss of habitat as a result of conversion; (b) increased limitations to

animal movement, population and gene flow (Bar-Massada et al., 2014; Mcpearson et al., 2013)—From a landscape continuity perspective, the larger and more massive continuous built-up area that develops at the central region of the study area (primarily the Center district) in the unregulated scenario (Fig. 3a), as compared with the regulated scenario (Fig. 3b), might pose a more severe limitation to the movement and dispersal of many species between the northern and southern parts of the study area; (c) biological invasions—these are expected to be facilitated by increased fragmentation and proximity of natural habitats to built-up areas (Alberti, 2005; Bar-Massada et al., 2014); and (d) altered community structure and interactions—in Israel some species such as the Golden Jackal (*Canis aureus*), Eastern European Hedgehog (*Erethizon dorsatum*) and Egyptian mongoose (*Herpestes ichneumon*) utilize human resources and the presence of their populations in the vicinity of human settlements is increased. Other species, such as the Mountain Gazelle (*Gazella gazella gazella*) are sensitive to the presence of human settlements and tend to avoid them (Berg et al., 2015). The differential sensitivity of species to human settlements can alter the community structure, and interactions such as predator-prey dynamics, competition, disease transmission (Bar-Massada et al., 2014).

Overall, our results indicating the favorability of the regulated scenario (which includes growth management policy implementation) are consistent with the findings of other simulation (Mitsova et al., 2000; Robinson and Brown, 2009; Sohl et al., 2012) and empirical (Jongsomjit et al., 2012; Merenlender et al., 2009; Suarez-Rubio et al., 2013) studies that have examined the ecological impact of different urban forms. However, as noted above, a major caveat of the regulated scenario is its effectiveness in lower development rates—in development rates that are similar to those observed between 1998 and 2007, the regulated scenario had no obvious advantage over the unregulated scenario (Fig. 5). Moreover, the extent of developed areas in close proximity to protected areas (500 m) was similar in both scenarios also in higher development rates (Fig. 5e). This means that the regulated scenario did not prevent development near protected areas more than the unregulated scenario. Increased proximity between protected areas and built-up areas can result in conflicts between stakeholders and hamper conservation (Hansen and Defries, 2007; McDonald et al., 2008). Thus, the regulated scenario could potentially result in an adverse effect on the functioning and performance of protected areas, particularly since it directs more development to the North and South districts which contain more protected areas. Unintentional adverse effects of growth management plans have been shown elsewhere. Gimmi et al. (2011) showed that in the U.S., the establishment of national parks resulted in accelerated growth rates in their surrounding areas. Robinson et al. (2005) showed that in the Puget Sound Region, growth management policies with the objective of protecting natural habitats did not prevent low-density development, and the unintended outcome was increased fragmentation of rural and natural areas.

## 5. Conclusions

We compared two alternative urban development scenarios at a regional scale over a range of increasing development rates. Compared to other studies, a notable distinction of our methodology is that rather than analyzing a single instance of development, we simulated each scenario over a range of development rates. This approach has an advantage over the comparison of two single future states, since it allowed us to address a dimension of uncertainty regarding the expected rate of development in the study area. Development rates can be influenced by factors such as population growth and changes in income and standard of living (Frenkel, 2004b; Verburg et al., 2006). Estimates for these factors often vary

and, furthermore, they could also be affected by unpredictable dramatic events or crises (e.g., the massive influx of immigrants from the Former Soviet Union to Israel in the beginning of the 1990s; see Alterman, 1995; Frenkel, 2004a). From a practical perspective, assessing a range of possible development rates can provide planners with insights regarding the trajectories of proposed plans and their potential impact, and thus help to reduce some of the uncertainties associated with this type of decision-making.

We found that regardless of its spatial pattern, increasing rates of development were expected to have negative ecological consequences at the regional scale. It has been pointed out that analyses at broader scales, e.g., regional or national (such as ours) are important since biodiversity conservation targets are commonly set at broader scales and since information from finer scales (e.g., city or neighborhood) “is not necessarily generalizable to larger-scale analyses and will not be helpful for determining how a range of land used should be arranged across a landscape.” (Lin and Fuller, 2013). While our study area is relatively similar in size to a number of other case-studies that have compared the preservation of open space and landscape-scale ecological impacts of urban growth scenarios using simulations (app. 9,045 km<sup>2</sup> in Thorne et al., 2013; app. 9,180 km<sup>2</sup> in Villarreal et al., 2013), our case-study is relatively unique since it involves the comparison of policies determined at a national scale rather than the district or city level.

Overall, we found that the regulated scenario, which included the implementation of growth management policies, was more beneficial from a conservation perspective. In this respect, our study supports the findings of other studies that have found that management steps for containing urban sprawl are expected to be more beneficial for conservation (e.g., Martinuzzi et al., 2013, in the case of freshwater ecosystems and aquatic biodiversity conservation in the contiguous U.S.; and Sushinsky et al., 2013, in the case of local extinctions of bird species in Brisbane, Australia). We did however find limitations to the regulated scenario, which is based on the national outline plan: under low development rates it performed very similarly to the unregulated scenario and it did not restrict or prevent development in proximity to protected areas also in higher development rates. We therefore propose that additional policies and measures are needed in order to minimize ecological damage at lower development rates. Two possible options are to define and enforce no-development buffers around protected areas, and to establish a new type of protected area, which will provide protection also to landscapes with mixed land cover classes, such as agro-ecosystems. More generally, we recommend that growth management plans incorporate measurable and quantitative conservation objectives, rather than abstract definitions, such as “maintaining connectivity” or “minimizing habitat loss”.

## Acknowledgments

We thank D. Orenstein for his thoughtful input during the study. We also thank the two anonymous reviewers for the careful reading and valuable comments which helped to improve this manuscript. This work was supported by the Israeli Ministry of Science and Technology TASHTIOT program.

## Appendix A.

### Weights of Evidence—method

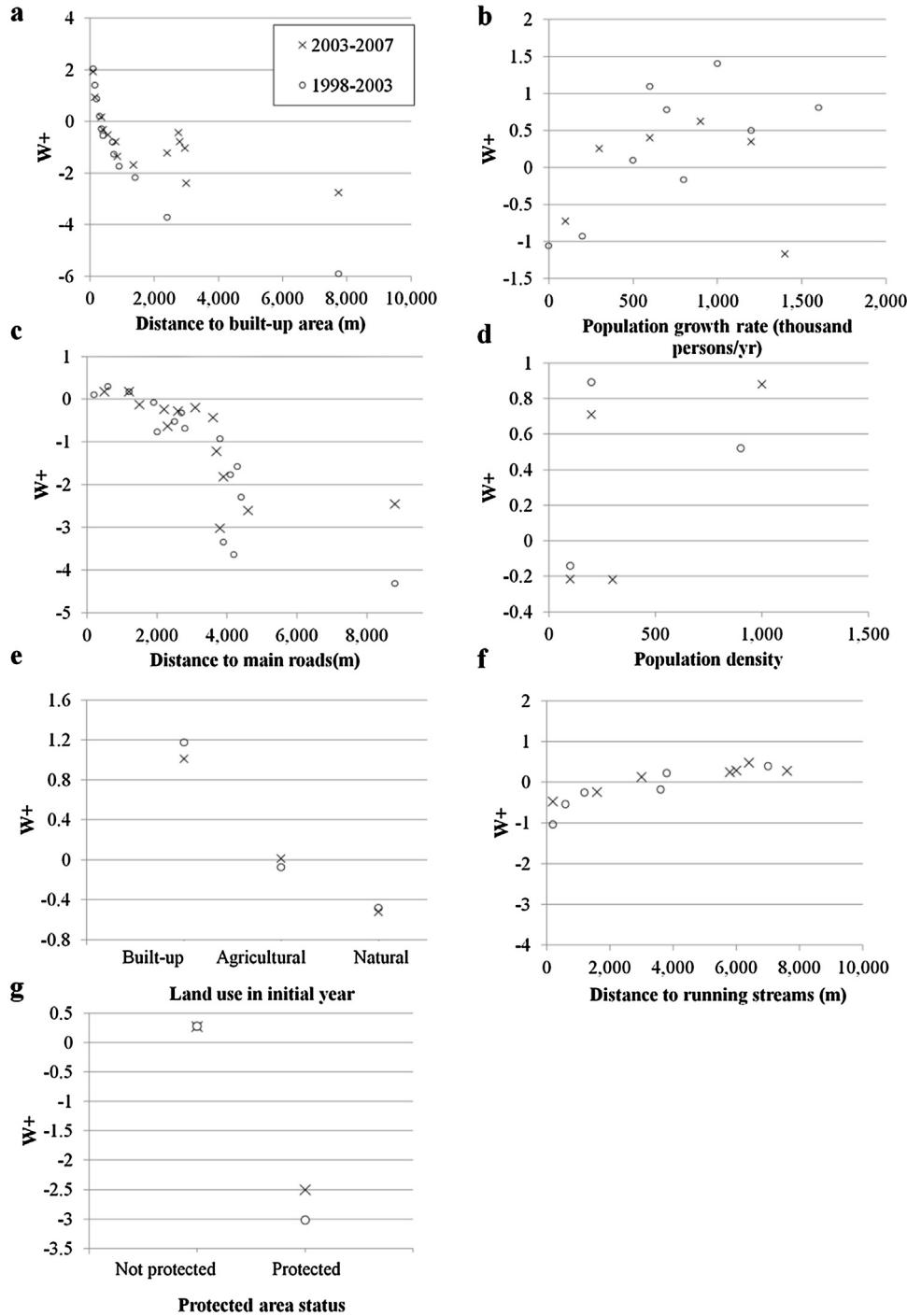
In the land cover change context, the Weight of Evidence method (Bonham-Carter, 1994) is used to detect the favorability of a land cover change in relation to the potential evidences (driving factors of change). The weights are estimated from the measured

association between land cover change events (evidence) and the values of the driving factor maps (predictors). The weight (influence) of each variable on a transition (land cover change event) is calculated independently of a combined solution (Maeda et al., 2011; Soares-Filho et al., 2009, 2002).

Here we describe the method briefly, based on the explanation in Maeda et al. (2011) and Ximenes et al. (2011). More detailed explanations can be found in the DINAMICA manual (Soares-Filho et al., 2009) and in the supplementary information of Soares-Filho et al. (2010).

Eq. (1) serves to calculate the spatial probability of a transition (Maeda et al., 2011; Ximenes et al., 2011):

$$P\left(\frac{T_i^\alpha}{V_i^1, \dots, V_i^{m_\alpha}}\right) = \frac{O(T_i^\alpha) \times e^{\sum_{v=1}^{m_\alpha} W_{i,v}^+}}{1 + \sum_{\alpha=1}^n O(T_i^\alpha) \times e^{\sum_{v=1}^{m_\alpha} W_{i,v}^+}} \quad (1)$$



**Fig. A1.** Weight of evidence coefficients for spatial drivers of change from open into built-up land for the calibration and validation periods: (a) distance to built-up area, (b) population growth rate in sub-district in the five years prior initial year, (c) distance to main roads, (d) population density in sub-district in initial year, (e) land-use in initial year, (f) distance to running streams, and (g) protected area status.

**Table A1**

Variables used as drivers of open-built transition in the spatial probability map.  $t_0$  is the initial year of the model (for the calibration—1998, for validation—2003, for the scenario simulations—2007). All layers were provided as vector data and converted to raster format at a resolution of 50 m cell size. Abbreviations of sources: HUGIS—Hebrew University of Jerusalem GIS Center; CBS—Israel Central Bureau of Statistics; INPA—Israel Nature and Parks Authority; MOIN—Israel Ministry of Interior; JNF—Jewish National Fund.

Number	Variable	Data (Source)	Year	Variable data type	Publication(s) indicating importance of variable
1	Distance from major roads and highways	Major roads and highways (HUGIS)	2009	Continuous	Levin et al., 2007
2	Distance from major running streams	Major running streams (HUGIS)	2009	Continuous	Maruani and Amit-Cohen, 2009
3	Average Population growth in sub-district over five years prior to the initial year ( $t_0$ )	Sub-district borders (CBS)	2009	Continuous	Orenstein and Hamburg, 2010
4	Population density in sub-district at the initial year ( $t_0$ )	Population data (CBS)	2003–2007	Continuous	Orenstein and Hamburg, 2010
5	Land use	Sub-district borders population data (CBS)	2009	Categorical	Frenkel, 2004a, b; Orenstein and Hamburg, 2010; Alfasi et al., 2012
6	Distance from built-up areas	Vegetation and land cover (INPA)	1995	Continuous	Benguigui et al., 2001; Benguigui and Czamanski, 2004
7	Protection status	Land-use (CBS)	2002	Categorical	Frenkel, 2004a, b; Orenstein and Hamburg, 2010; Alfasi et al., 2012
		Built-up areas (MOIN)	2007		
		Protected areas (INPA and JNF)	2009		

where  $P$  is the probability of transition in a cell;  $i$  notes the position of a cell in the study area;  $\alpha$  represents a type of land cover transition,  $\eta$  represents the total number of transition types (in our case there is one type of transition—from open into built-up land);  $V_i^1$  and  $V_i^{m_\alpha}$  are the first and  $m$ th variable observed in cell  $i$ , respectively;  $O(T_i^\alpha)$  is the odds ratio of transition  $T^\alpha$  in the  $i$ th cell (the probability of  $T_i^\alpha$  divided by the complementary probability

$\bar{T}_i^\alpha$ , i.e., the probability that  $T^\alpha$  will not occur in the  $i$ th cell);  $W_{i,v}^+$  corresponds to the positive weight of evidence for the  $i$ th cell with respect to the  $v$ th variable, and is defined by the following Eq. (2):

$$W_{i,v}^+ = \log_e = \frac{P(V_i^{m_\alpha}/T_i^\alpha)}{P(V_i^{m_\alpha}/\bar{T}_i^\alpha)} \quad (2)$$

The term in the numerator found within the natural logarithm function on the right hand of the equation is the probability of occurrence of the  $m$ th variable range observed in cell  $i$ , used to explain transition  $\alpha$  given the prior presence of transition  $T_i^\alpha$ —which is calculated by dividing the number of cells where both  $V_i^{m_\alpha}$  and  $T_i^\alpha$  by the total number of cells where  $T_i^\alpha$  is found. The term in the denominator represents the probability of occurrence of the  $m$ th variable range observed in cell  $i$ , used to explain transition  $T_i^\alpha$  given the previous absence of transition  $T_i^\alpha$ —calculated by dividing the number of cells where both  $V_i^{m_\alpha}$  and  $\bar{T}_i^\alpha$  are found by the total number of cells where  $\bar{T}_i^\alpha$  is not found.

$W^+$  values represent the degree of association between a given transition and a certain variable range. Positive  $W^+$  values repre-

sent a greater probability of a certain transition, while negative values of  $W^+$  indicate a negative association between the given transition and variable range (e.g., inhibition of a transition). near zero values indicate no association (Silvestrini et al., 2011).

The input variables which we used as input to the Weights of Evidence method and produce spatial probability maps are listed in Table A1 along with their source.

The application of the method requires two preliminary stages: (1) Categorizing continuous variables. In order to categorize continuous variables (Table 1A) we implemented a categorization method that is included in DINAMICA-EGO and was adapted from Agterberg and Bonham-Carter (1990) and Goodacre et al. (1993); (2) Ensuring spatial independence between the input variables. We tested the pairwise correlations between the variables using Cramer's coefficient ( $V$ ) and the Joint Information Uncertainty ( $U$ ) (Bonham-Carter, 1994). The values of these tests are between 0 and 1, representing independence to full association of the pair of maps, respectively. There are no significance tests for these measures and generally values  $< 0.5$  imply weaker association.

#### Weights of evidence—results

Almost all values of pairwise correlation between the variables used as spatial drivers of urban development were lower than 0.5, implying high independence of all these variables (Table A2). The highest correlation was between population growth rate and population density (Joint Information Uncertainty = 0.64), however the corresponding value of Cramer's coefficient for this pair of vari-

**Table A2**

Correlation between spatial variables used for the Weights of Evidence method (Cramer's coefficient below the diagonal and Joint Information Uncertainty values above the diagonal).

Cramer's Coefficient/Joint Information Uncertainty	Distance to built-up area	Protected area status	Distance to main roads	Distance to running stream	Land use in $t_0$	Average population growth rate in the five years prior to $t_0$	Population density in $t_0$
Distance to built-up area	—	0.03	0.07	0.04	0.07	0.03	0.03
Protected area status	0.25	—	0.01	0.00	0.018	0.02	0.01
Distance to main roads	0.18	0.15	—	0.03	0.01	0.01	0.01
Distance to running stream	0.15	0.08	0.13	—	0.02	0.13	0.05
Land use in $t_0$	0.30	0.53	0.08	0.14	—	0.03	0.03
Average population growth rate in the five years prior to $t_0$	0.15	0.19	0.08	0.35	0.16	—	0.40
Population density in $t_0$	0.17	0.14	0.10	0.215	0.14	0.64	—

ables was <0.5 (0.4). We therefore decided to include both variables (Maeda et al., 2011).

The Weights of Evidence method allowed us to analyze the effect of each spatial variable on the transition probability from open into built-up land. The major findings are shown in Fig. A1 and were: (a) the probability of conversion from open to built-up land decreased with distance (particularly above 200 m) from existing built-up land in both periods (1998–2003 and 2003–2007) as indicated by relatively high  $W^+$  values in shorter distances; (b) Development was more likely to occur in sub-district that experienced higher levels of population growth in the five years prior to the initial year of the simulation period (>500 thousand persons/year); (c) Areas in proximity to main roads (up to approximately 1,200 m) were more likely to undergo development; (d) Population density at the sub-district level did not have a consistent and clear effect on development; (e) Development was more likely to occur on areas with agricultural land use than on natural areas; (f) development was less likely to occur in proximity to running streams; (g) development was less likely to occur in protected areas.

## Appendix B.

**Table B1.**

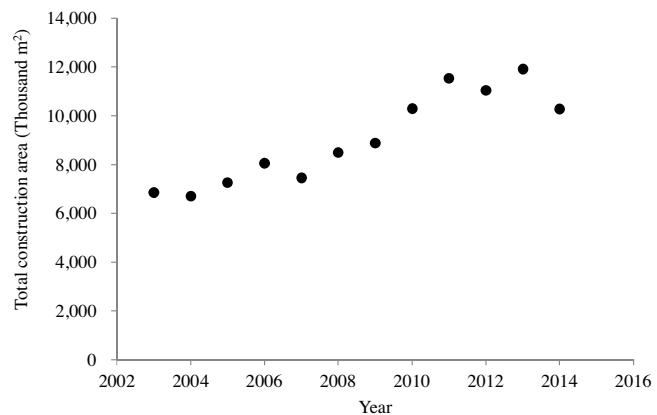
**Table B1**

Parameters used in the simulation of each scenario at the reference development rate. In the remaining simulations for each scenario, all parameters remained identical except for the transition probability which was increased by 100% each time.

Scenario	Parameter	District				
		South	Haifa	Jerusalem	Center	North
Reference	Mean patch size (Ha) (patcher)	12.73	13.35	6.5	6	5
	Mean patch size (Ha) (expander)	12.73	13.35	7.61	8.74	6.41
	Patch size variance	1,801,500	1,848,020	370,320	350,360	70,740
	Isometry	2	2	2	2	2
	Patcher/expander ratio	0.4	0.64	0.3	0.6	0.7
	Transition probability ( $\times 10^4$ )	5.79	14.41	9.32	31.04	7.54
Unregulated	Mean patch size (Ha) (patcher)	6.4	6.7	3.3	3.0	2.5
	Mean patch size (Ha) (expander)	6.4	6.7	3.8	4.4	3.2
	Patch size variance	1,801,500	1,848,020	370,320	350,360	70,740
	Isometry	2	2	2	2	2
	Patcher/expander ratio	0.6	0.96	0.45	0.9	1
	Transition probability ( $\times 10^4$ )	7.24	18.01	11.64	38.80	9.43
Regulated	Mean patch size (Ha) (patcher)	31.8	33.4	16.3	15	12.5
	Mean patch size (Ha) (expander)	31.8	33.4	19.0	21.9	16.0
	Patch size variance	1,801,500	1,848,020	370,320	350,360	70,740
	Isometry	2	2	2	2	2
	Patcher/expander ratio	0.2	0.32	0.15	0.3	0.35
	Transition probability ( $\times 10^4$ )	7.48	8.94	5.71	16.93	6.47

## Appendix C.

**Fig. C1.**



**Fig. C1.** Annual total construction area in Israel between 2003 and 2014. Source: Central Bureau of Statistics of Israel, 2015. Table 22.6. Construction area, by purpose [WWW Document]. Statistical Abstract of Israel 2015. URL [http://www1.cbs.gov.il/shnaton66/st22\\_06.pdf](http://www1.cbs.gov.il/shnaton66/st22_06.pdf). (accessed 1.13.16).

## References

- Achiron-Frumkin T., 2011. Report on the state of nature 2010. Hamaarag—Israel's National Ecosystem Assessment Program, sponsored by the Israel Academy of Sciences and Humanities, Jerusalem, Israel. (In Hebrew).
- Agterberg, F.P., Bonham-Carter, G.F., 1990. Deriving weights of evidence from geoscience contour maps for the prediction of discrete events. *Proceedings of the XXII International Symposium AP-COM*, 381–395.
- Alberti, M., 2005. The effects of urban patterns on ecosystem function. *Int. Reg. Sci. Rev.* 28, 168–192, <http://dx.doi.org/10.1177/0160017605275160>.
- Alfasi, N., Almagor, J., Benenson, I., 2012. The actual impact of comprehensive land-use plans: insights from high resolution observations. *Land Use Policy* 29, 862–877, <http://dx.doi.org/10.1016/j.landusepol.2012.01.003>.
- Almeida, C.M., Gleriani, J.M., Castejon, E.F., Soares-Filho, B.S., 2008. Using neural networks and cellular automata for modelling intra-urban land-use dynamics. *Int. J. Geogr. Inf. Sci.* 22, 943–963, <http://dx.doi.org/10.1080/13658810701731168>.
- Alterman, R., 1995. Can planning help in time of crisis? planners' responses to Israel's recent wave of mass immigration. *J. Am. Plan. Assoc.* 61, 156–177, <http://dx.doi.org/10.1080/01944369508975630>.
- Angel, S., Sheppard, S.C., Civco, D.L., Buckley, R., Chabaeva, A., Gitlin, L., Kraley, A., Parent, J., Perlin, M., 2005. *The Dynamics of Global Urban Expansion, Transport and Urban Development Department. The World Bank*, Washington, D.C.
- Angel, S., Parent, J., Civco, D.L., 2012. The fragmentation of urban landscapes: global evidence of a key attribute of the spatial structure of cities, 1990–2000. *Environ. Urban* 24, 249–283, <http://dx.doi.org/10.1177/0956247811433536>.
- Assif, S., Shachar, A., 2005. *TAMA 35—Ikarei H'Tokhnit (NOP 35—Plan Highlights. Planning Authority—Israel Ministry of Interior, Jerusalem, Israel (In Hebrew)*.
- Ball, I.R., Possingham, H.P., Watts, M., 2009. *Marxan and relatives: software for spatial conservation prioritisation*. In: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), *Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools*. Oxford University Press, Oxford, UK, pp. 185–195.
- Bar-Massada, A., Radeloff, V.C., Stewart, S.I., 2014. Biotic and abiotic effects of human settlements in the wildland-urban interface. *Bioscience* 64, 429–437, <http://dx.doi.org/10.1093/biosci/biu039>.
- Ben David, I., Avni, N., 2013. Israel's Planning and Building Threats to Open Spaces—Annual Report for 2013. Tel Aviv, Israel. (In Hebrew).
- Benguigui, L., Czamanski, D., 2004. *Simulation analysis of the fractality of cities. Geogr. Anal.* 36, 69–84.
- Benguigui, L., Czamanski, D., Marinov, M., 2001. The dynamics of urban morphology: the case of Petah Tikvah. *Environ. Plan. B Plan. Des.* 28, 447–460, <http://dx.doi.org/10.1068/b2703>.
- Berg, N., Drori, R., Dan, H., Perlberg, A., Soreq, M., 2015. State of the Nature Report 2015. Jerusalem, Israel. (In Hebrew).
- Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists: Modelling with GIS. Pergamon, New York, NY.
- Brueckner, J.K., 2000. *Urban sprawl: diagnosis and remedies. Int. Reg. Sci. Rev.* 23, 160–171.
- Bryant, M.M., 2006. Urban landscape conservation and the role of ecological greenways at local and metropolitan scales. *Landsc. Urban Plan.* 76, 23–44, <http://dx.doi.org/10.1016/j.landurbplan.2004.09.029>.
- Central Bureau of Statistics of Israel, 2015. Table 22.6. Construction area, by purpose [WWW Document]. Statistical Abstract of Israel 2015. URL . (accessed 1.13.16).
- Chace, J.F., Walsh, J.J., 2006. Urban effects on native avifauna: a review. *Landsc. Urban Plan.* 74, 46–69, <http://dx.doi.org/10.1016/j.landurbplan.2004.08.007>.
- Chamberlain, D.E., Cannon, A.R., Toms, M.P., Leech, D.I., Hatchwell, B.J., Gaston, K.J., 2009. Avian productivity in urban landscapes: a review and meta-analysis. *Ibis (Lond. 1859)* 151, 1–18, <http://dx.doi.org/10.1111/j.1474-919X.2008.00899.x>.
- Cohen, A., Tur'el, Y., Kaplan, M., 2010. National Outline Plan 35 – accompaniment, monitoring, and update – stage 3 report. Jerusalem, Israel. (In Hebrew).
- Cohen, B., 2006. Urbanization in developing countries: current trends, future projections, and key challenges for sustainability. *Technol. Soc.* 28, 63–80, <http://dx.doi.org/10.1016/j.techsoc.2005.10.005>.
- Couch, C., Karecha, J., 2006. Controlling urban sprawl: some experiences from Liverpool. *Cities* 23, 353–363, <http://dx.doi.org/10.1016/j.cities.2006.05.003>.
- Czamanski, D., Benenson, I., Malkinson, D., Marinov, M., Roth, R., Wittenberg, L., 2008. Urban sprawl and ecosystems—can nature survive? *Int. Rev. Environ. Resour. Econ.* 2, 321–366, <http://dx.doi.org/10.1561/101.00000019>.
- Dallimer, M., Tang, Z., Bibby, P.R., Brindley, P., Gaston, K.J., Davies, Z.G., 2011. Temporal changes in greenspace in a highly urbanized region. *Biol. Lett.* 7, 763–766.
- De Rezende, C.L., Uezu, A., Scarano, F.R., Araujo, D.S.D., 2015. Atlantic forest spontaneous regeneration at landscape scale. *Biodivers. Conserv.* 24, 2255–2272, <http://dx.doi.org/10.1007/s10531-015-0980-y>.
- Dolev, A., Carmel, Y., 2009. Distribution of threatened-unprotected vertebrates as a basis for conservation planning. *Isr. J. Ecol. Evol.* 55, 117–132, <http://dx.doi.org/10.1560/jee.55.2.117>.
- European Environmental Agency, 2006. *Urban Sprawl in Europe—the Ignored Challenge. EEA Report 10/2006*, Copenhagen, Denmark.
- Ewing, R., 1997. Is Los Angeles-style sprawl desirable? *J. Am. Plan Assoc.* 63, 107–126, <http://dx.doi.org/10.1080/0194436970897528>.
- Ewing, R., 2008. Characteristics, causes and effects of sprawl: a literature review. In: Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., ZumBrunnen, C., Simon, U. (Eds.), *Urban Ecology*. Springer Science+Business Media LLC, New York, NY, pp. 519–535.
- Frenkel, A., Orenstein, D., 2011. A pluralistic approach to defining and measuring urban sprawl. In: Yang, X. (Ed.), *Urban Remote Sensing: Monitoring, Synthesis and Modeling in the Urban Environment*. John Wiley & Sons, Ltd, Chichester, UK, pp. 165–183, <http://dx.doi.org/10.1002/9780470979563.ch12>.
- Frenkel, A., Orenstein, D.E., 2012. Can urban growth management work in an era of political and economic change? *J. Am. Plan. Assoc.* 78, 16–33, <http://dx.doi.org/10.1080/01944363.2011.643533>.
- Frenkel, A., 2004a. The potential effect of national growth-management policy on urban sprawl and the depletion of open spaces and farmland. *Land Use Policy* 21, 357–369, <http://dx.doi.org/10.1016/j.landusepol.2003.12.001>.
- Frenkel, A., 2004b. A land-consumption model: its application to Israel's future spatial development. *J. Am. Plan. Assoc.* 70, 453–470, <http://dx.doi.org/10.1080/01944360408976394>.
- Gagné, S.A., Fahrig, L., 2010. The trade-off between housing density and sprawl area: Minimising impacts to forest breeding birds. *Basic Appl. Ecol.* 11, 723–733, <http://dx.doi.org/10.1016/j.baae.2010.09.001>.
- Gimmi, U., Schmidt, S.L., Hawbaker, T.J., Alcántara, C., Gafvert, U., Radeloff, V.C., 2011. Increasing development in the surroundings of U.S. national park service holdings jeopardizes park effectiveness. *J. Environ. Manage.* 92, 229–239, <http://dx.doi.org/10.1016/j.jenvman.2010.09.006>.
- Glaeser, E.L., Kahn, M.E., 2003. Sprawl and urban growth. In: Henderson, J.V., Thisse, J. (Eds.), *Handbook of Regional and Urban Economics*. Elsevier, Amsterdam, Netherlands, pp. 2481–2527.
- Goodacre, A.K., Bonham-Carter, G.F., Agterberg, F.P., Wright, D.F., 1993. *A statistical analysis of the spatial association of seismicity with drainage and magnetic anomalies in western Quebec. Tectonophysics* 217, 285–305.
- Gordon, P., Richardson, H.W., 1997. Are compact cities a desirable planning goal? *J. Am. Plan. Assoc.* 63, 95–106, <http://dx.doi.org/10.1080/0194436970897527>.
- Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. *Science* 319, 756–760, <http://dx.doi.org/10.1126/science.1150195>.
- Gustafson, E.J., 1998. *Quantifying Landscape spatial pattern: what is the state of the art? Ecosystems* 1, 143–156.
- Hagen-Zanker, A., Lajoie, G., 2008. Neutral models of landscape change as benchmarks in the assessment of model performance. *Landscape and Urban Planning* 86, 284–296, <http://dx.doi.org/10.1016/j.landurbplan.2008.04.002>.
- Hansen, A.J., Defries, R., 2007. Ecological mechanisms linking protected areas to surrounding lands. *Ecol. Appl.* 17, 974–988.
- Hasse, J.E., Lathrop, R.G., 2003. Land resource impact indicators of urban sprawl. *Appl. Geogr.* 23, 159–175, <http://dx.doi.org/10.1016/j.apgeog.2003.08.002>.
- Ikin, K., Barton, P.S., Knight, E., Lindenmayer, D.B., Fischer, J., Manning, A.D., 2014. Bird community responses to the edge between suburbs and reserves. *Oecologia* 174, 545–557, <http://dx.doi.org/10.1007/s00442-013-2793-6>.
- Irwin, E.G., Bockstael, N.E., 2007. The evolution of urban sprawl: evidence of spatial heterogeneity and increasing land fragmentation. *Proc. Natl. Acad. Sci. U. S. A.* 104, 20672–20677, <http://dx.doi.org/10.1073/pnas.070552105>.
- Jongsomjit, D., Stralberg, D., Gardali, T., Salas, L., Wiens, J., 2012. Between a rock and a hard place: the impacts of climate change and housing development on breeding birds in California. *Landscape and Urban Planning* 107, 187–200, <http://dx.doi.org/10.1016/j.landurbplan.2012.09.025-1>.
- Levin, N., Lahav, H., Ramon, U., Heller, A., Nizry, G., Tsoar, A., Sagi, Y., 2007. Landscape continuity analysis: a new approach to conservation planning in Israel. *Landscape and Urban Planning* 79, 53–64, <http://dx.doi.org/10.1016/j.landurbplan.2006.04.001>.
- Lin, B.B., Fuller, R.A., 2013. Sharing or sparing? How should we grow the world's cities? *J. Appl. Ecol.* 50, 1161–1168, <http://dx.doi.org/10.1111/1365-2664.12118>.
- Maeda, E.E., De Almeida, C.M., Carvalho Ximenes, A., De Formaggio, A.R., Shimabukuro, Y.E., Pellikka, P., 2011. Dynamic modeling of forest conversion: simulation of past and future scenarios of rural activities expansion in the fringes of the Xingu national park, Brazilian Amazon. *Int. J. Appl. Earth Obs. Geoinf.* 13, 435–446, <http://dx.doi.org/10.1016/j.jag.2010.09.008>.
- Martinuzzi, S., Januchowski-Hartley, S.R., Pracheil, B.M., McIntyre, P.B., Plantinga, A.J., Lewis, D.J., Radeloff, V.C., 2013. Threats and opportunities for freshwater conservation under future land use change scenarios in the United States. *Glob. Chang. Biol.* 20, 1–12, <http://dx.doi.org/10.1111/gcb.12383>.
- Mariani, T., Amit-Cohen, I., 2009. The effectiveness of the protection of riparian landscapes in Israel. *Land use policy* 26, 911–918, <http://dx.doi.org/10.1016/j.landurbplan.2008.11.002>.
- Mazor, A., 1993. Israel 2020: Master Plan for Israel During the 21st Century. The Technion, Haifa. (In Hebrew).
- McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E., 2002. FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts.
- McDonald, R.I., Kareiva, P., Forman, R.T.T., 2008. The implications of current and future urbanization for global protected areas and biodiversity conservation. *Biol. Conserv.* 141, 1695–1703, <http://dx.doi.org/10.1016/j.biocon.2008.04.025>.
- Mcphearson, T., Auch, R., Alberti, M., 2013. Urbanization, biodiversity and ecosystem services: challenges and opportunities. In: Elmquist, T., Frangkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*. Springer Netherlands, Dordrecht, Netherlands, pp. 279–286, <http://dx.doi.org/10.1007/978-94-007-7088-1>.

- Merenlender, A.M., Reed, S.E., Heise, K.L., 2009. Exurban development influences woodland bird composition. *Landsc. Urban Plan.* 92, 255–263, <http://dx.doi.org/10.1016/j.landurbplan.2009.05.004>.
- Mitsova, D., Shuster, W., Wang, X., 2011. A cellular automata model of land cover change to integrate urban growth with open space conservation. *Landsc. Urban Plan.* 99, 141–153, <http://dx.doi.org/10.1016/j.landurbplan.2010.10.001>.
- Mo, U., Mortberg, U., Wallentinus, H.-G., 2000. Red-listed forest bird species in an urban environment—assessment of green space corridors. *Landsc. Urban Plan.* 50, 215–226.
- Montgomery, M.R., 2008. The urban transformation of the developing world. *Science* 319, 761–764, <http://dx.doi.org/10.1126/science.1153012>.
- Nti, I.K., Sallis, P., 2014. *Geospatial Process Modelling for Land Use Cover Change*. In: Ames, D.P., Quinn, N.W.T., Rizzoli, A.E. (Eds.), *Proceedings of the 7th International Congress on Environmental Modelling and Software*.
- Orenstein, D.E., Hamburg, S.P., 2010. Population and pavement: population growth and land development in Israel. *Popul. Environ.* 31, 223–254, <http://dx.doi.org/10.1007/s11111-010-0102-4>.
- Orenstein, D.E., Frenkel, A., Jahshan, F., 2014. Methodology matters: measuring urban spatial development using alternative methods. *Environ. Plan. B Plan. Des.* 41, 3–23.
- Pautasso, M., Böhning-Gaese, K., Clergeau, P., Cueto, V.R., Dinetti, M., Fernández-Juricic, E., Kaisanlahti-Jokimäki, M.-L., Jokimäki, J., McKinney, M.L., Sodhi, N.S., Storch, D., Tomiajlojc, L., Weisberg, P.J., Woinarski, J., Fuller, R.A., Cantarella, E., 2011. Global macroecology of bird assemblages in urbanized and semi-natural ecosystems. *Glob. Ecol. Biogeogr.* 20, 426–436, <http://dx.doi.org/10.1111/j.1466-8238.2010.00616.x>.
- Radeloff, V.C., Hammer, R.B., Stewart, S.I., 2005. Rural and suburban sprawl in the U.S. midwest from 1940 to 2000 and its relation to forest fragmentation. *Conserv. Biol.* 19, 793–805, <http://dx.doi.org/10.1111/j.1523-1739.2005.00387.x>.
- Razin, E., Rosentraub, M., 2000. Are fragmentation and sprawl interlinked?: North American evidence. *Urban Aff. Rev.* 35, 821–836, <http://dx.doi.org/10.1177/10780870022184697>.
- Ries, L., Fletcher, R.J., Battin, J., Sisk, T.D., 2004. Ecological responses to habitat edges: mechanisms, models, and variability explained. *Annu. Rev. Ecol. Evol. Syst.* 35, 491–522, <http://dx.doi.org/10.1146/annurev.ecolsys.35.112202.130148>.
- Robinson, D.T., Brown, D.G., 2009. Evaluating the effects of land-use development policies on ex-urban forest cover: an integrated agent-based GIS approach. *Int. J. Geogr. Inf. Sci.* 23, 1211–1232.
- Robinson, L., Newell, J.P., Marzluff, J.M., 2005. Twenty-five years of sprawl in the seattle region: growth management responses and implications for conservation. *Landsc. Urban Plan.* 71, 51–72, <http://dx.doi.org/10.1016/j.landurbplan.2004.02.005>.
- Salonen, M., Maeda, E.E., Toivonen, T., 2014. Evaluating the Impact of distance measures on deforestation simulations in the Fluvial Landscapes of Amazonia. *Ambio* 43, 779–790, <http://dx.doi.org/10.1007/s13280-013-0463-x>.
- Sandström, U.G., Angelstam, P., Mikusiński, G., 2006. Ecological diversity of birds in relation to the structure of urban green space. *Landsc. Urban Plan.* 77, 39–53, <http://dx.doi.org/10.1016/j.landurbplan.2005.01.004>.
- Schaffer, G., Levin, N., 2014. Mapping human induced landscape changes in Israel between the end of the 19th century and the beginning of the 21th century. *J. Landsc. Ecol.* 7, 110–145.
- Seto, K.C., Fragkias, M., Guneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. *PLoS One* 6, 1–9.
- Shi, Y., Sun, X., Zhu, X., Li, Y., Mei, L., 2012. Characterizing growth types and analyzing growth density distribution in response to urban growth patterns in peri-urban areas of Lianyungang City. *Landsc. Urban Plan.* 105, 425–433, <http://dx.doi.org/10.1016/j.landurbplan.2012.01.017>.
- Silvestrini, R.A., Soares-Filho, B.S., Nepstad, D., Coe, M., Rodrigues, H., Assunção, R., 2011. Simulating fire regimes in the Amazon in response to climate change and deforestation. *Ecol. Appl.* 21, 1573–1590.
- Soares-Filho, B.S., Pennachin, C.L., Cerqueira, G., 2002. DINAMICA—a stochastic cellular automata model designed to simulate the landscape dynamics in an amazonian colonization frontier. *Ecol. Model.* 154, 217–235.
- Soares-Filho, B.S., Rodrigues, H.O., Costa, W.L., 2009. Modeling Environmental Dynamics with Dinamica EGO. *Belo Horizonte/Minas Gerais, Brazil*.
- Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R., Maretti, C., 2010. Role of Brazilian Amazon protected areas in climate change mitigation. *Proc. Natl. Acad. Sci.* 107, 10821–10826, <http://dx.doi.org/10.1073/pnas.0913048107>.
- Soares-Filho, B., Rodrigues, H., Follador, M., 2013. A hybrid analytical-heuristic method for calibrating land-use change models. *Environ. Model. Softw.* 43, 80–87, <http://dx.doi.org/10.1016/j.envsoft.2013.01.010>.
- Sohl, T.L., Sleeter, B.M., Sayler, K.L., Bouchard, M.A., Reker, R.R., Bennett, S.L., Sleeter, R.R., Kanengieter, R.L., Zhu, Z., 2012. Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States. *Agric. Ecosyst. Environ.* 153, 1–15, <http://dx.doi.org/10.1016/j.agee.2012.02.019>.
- Suarez-Rubio, M., Wilson, S., Leimgruber, P., Lookingbill, T., 2013. Threshold responses of forest birds to landscape changes around exurban development. *PLoS One* 8, 1–11, <http://dx.doi.org/10.1371/journal.pone.0067593>.
- Sushinsky, J.R., Rhodes, J.R., Possingham, H.P., Gill, T.K., Fuller, R.A., 2013. How should we grow cities to minimize their biodiversity impacts? *Glob. Chang. Biol.* 19, 401–410, <http://dx.doi.org/10.1111/gcb.12055>.
- Thorne, J.H., Santos, M.J., Bjorkman, J.H., 2013. Regional assessment of urban impacts on landcover and open space finds a smart urban growth policy performs little better than business as usual. *PLoS One* 8, e65258, <http://dx.doi.org/10.1371/journal.pone.0065258>.
- Troupin, D., Carmel, Y., 2014. Can agro-ecosystems efficiently complement protected area networks? *Biol. Conserv.* 169, 158–166, <http://dx.doi.org/10.1016/j.biocon.2013.11.009>.
- Verburg, P.H., Schulp, C.J.E., Witte, N., Veldkamp, A., 2006. Downscaling of land use change scenarios to assess the dynamics of European landscapes. *Agric. Ecosyst. Environ.* 114, 39–56, <http://dx.doi.org/10.1016/j.agee.2005.11.024>.
- Villarreal, M.L., Norman, L.M., Boykin, K.G., Wallace, C.S.A., 2013. Biodiversity losses and conservation trade-offs: assessing future urban growth scenarios for a North American trade corridor. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* 9, 90–103, <http://dx.doi.org/10.1080/21513732.2013.770800>.
- Weil, G., Levin, N., 2015. Can siting algorithms assist in prioritizing for conservation in a densely populated and land use allocated country?—Israel as a case study. *Isr. J. Ecol. Evol.* 61, 50–60, <http://dx.doi.org/10.1080/15659801.2015.1035858>.
- Ximenes, A., Almeida, C., Amaral, S., Escada, M.I.S., Aguiar, A.P.D., 2011. Spatial dynamic modelling of deforestation in the Amazon. In: Salcido, A. (Ed.), *Cellular Automata-Simplicity Behind Complexity*. InTech, pp. 47–66, <http://doi.org/10.5772/16137>.