Pigs in space:
an agent-based model of the penetration of wild boars into cities

Working draft

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Abstract:

Some consider the term urban nature an oxymoron. Their perception is that human activities fragment and eradicate open spaces in cities, resulting in dense built-up areas inhospitable to nature. Yet, there is ample evidence that cities are rich in certain plant and animal species. Based on optimal foraging theory, this paper presents an agent-based simulation model that suggests an explanation for the counterintuitive, ever growing presence of wild boars in some cities. We demonstrate that despite the shrinking of relatively large open space patches in Haifa, Israel, for wild boars the city's network of open spaces provides an attractive environment. The porosity of the urban fabric and the connectivity of open space patches in Haifa provide a "road network" that makes food throughout the city accessible at a relatively low search cost.

1. Introduction

Some consider the term *urban nature* an oxymoron. Viewed at a relatively crude geographic resolution, cities seem to expand in a fashion of a continuous wave from the center outward. The lay view is that the expansion of the built areas fragments and then eliminates open spaces and leaves no room for nature. Contrary to this view, the urban fabric contains gaps of open spaces of various extents, some discernable at higher resolutions (Czamanski et al., 2008; Toger et al., 2015), and others are large tracts of open spaces, such as city parks. Furthermore, there is ample empirical evidence that native flora and fauna inhabit cities (VanDruff & Rowse, 1986; Matthies et al., 2013). There are foxes and hedgehogs in London, moose and black bears in Montreal, coyotes in Chicago and wild boars in Berlin, San Jose and Haifa to mention just some examples. A recent survey conducted by Licoppe et al. (2013) indicates that the penetration of wild boars into urban areas is an increasing problem around the world. This phenomenon has been documented in over 60 urban areas, and causes concerns for wildlife management agencies and the local municipalities. In Haifa the population of wild boar (*Sus scrofa*) increased so much that the city's residents consider the animals a nuisance (Barshaw, 2012) and Haifa municipal government is considering various strategies in an attempt to control their numbers. Studies indicate that wild boars may have negative effects on plant and animal species richness and abundance (Massei & Genov, 2004). There is concern that their increasing number in cities may spread diseases (Gortázar et al 2007).

Why do large mammals living in large, open, semi-natural areas outside urban boundaries wonder among humans? This model aims to improve our understanding of the factors influencing penetration of wild boars into cities. There is ample literature on modeling animal movement in patchy environments (Fahrig 2007). To date no study has modeled wildlife movement within built-up areas. In this paper we present such a model and propose an explanation why cities are not inhospitable to some wildlife species.

We present a model that simulates the boar's daily movement for foraging in urban environments. By means of innovative simulation models we hypothesize that the expected energy expenditure of the wild boars and risk of urban foraging is relatively cheaper than in the periphery of cities. We demonstrate that despite the shrinking of relatively large open space patches, some urban morphologies, and Haifa's urban morphology in particular, leave a network of corridors and open patches that make the city quite porous enabling percolation by large mammals throughout the city (Toger et al., 2015). Haifa provides a “road network” that makes food, abundant in garbage bins that are distributed geographically in proportion to households, accessible at a relatively low search cost. We assert that the animal movement patterns in cities result from two opposing forces: attraction to resources of food and water and repulsion from disturbances that increase energy expenditure and perceived predation risk while foraging. Based on the optimal foraging theory, the paper presents an agent-based simulation model that illustrates an explanation for the counterintuitive, ever growing, presence of wild boars in cities with morphology such as that in Haifa. This study’s innovation is in combining the foraging optimization behavior with spatial modeling of animal movement in heterogeneous urban landscapes.

This paper includes 6 sections. Existing knowledge concerning wild boar foraging is outlined in the section 2. Section 3 presents the local context of our analysis and observations of wild boars presence in Haifa. Section 4 presents description of an agent-based model for simulating foraging of wild boars in a context of Haifa's urban morphology, landscape heterogeneity and distribution of food sources. In section 5 we present the results of our simulations. The final section 6 contains discussion and conclusions.

2. Movement and foraging behavior of wild boar – background

Based on a review of numerous animal movement studies Nathan et al. (2008) suggest a conceptual framework for empirical and modeling research for understanding the observed movement patterns of individual animals. In our research we follow Luniak (2004) and consider animal movement in response to available resources on the one hand, and mortality or predation risk on the other. Accordingly, resource abundance may be the reason that some bird and mammal species are thriving in urban environments more than in their native habitats (Hobbs et al., 2013). The process of urbanization of wild species (*synurbization*, Luniak, 2004) results in higher population densities, reduction of individual territory size, changed circadian activity patterns as well as changes in diet. Given the abundant food resources in Haifa, and the wild boar’s broad and omnivorous diet, we expect them to exhibit such urbanization tendencies.

Animal movement reflects trade-offs between costs in energy expenditure and risk of predation versus potential benefits of finding resources or mating partners in the target location (Fahrig, 2007). Some species make non-optimal movement decisions (Fahrig, 2007). However, wild boars are highly adaptive and opportunistic omnivores with high cognitive abilities. Thus the boars' penetration into cities should be viewed as having advantages in energy acquisition versus perceived risk and energy expenditure of the movement.

The wild boars' diet has a major impact on their foraging movement. Ballari and Barrios-García (2013) classified the feeding behavior of the wild boar into the following types: predation of vertebrates; rooting for rhizomes and invertebrates; foraging fungi, acorns, fruits and nuts; grazing; and scavenging (Thomson & Challies, 1988; Baubet et al., 2004). Studies assert that the impact of the wild boar rooting and predation activities on endangered flora and fauna can be negative and significant (Wilcox & Van Vuren, 2009; Bueno et al., 2011; Ballari & Barrios-García, 2013). Predation of vertebrates by wild boars in Mediterranean climate is most frequent during summer and fall (Wilcox & Van Vuren, 2009), due to the lack of protein in the available acorns in the semi-natural areas. Urban areas such as residential and commercial neighborhoods may provide additional food resources, supplementary to the food sources in areas covered by forest, scrubland, grassland, wetland, or agriculture. It follows that in a garbage-rich environment wild boars are in a surplus of calories. This can be considered the fundamental reason for their presence in cities (Licoppe et al., 2013). However, the spatial incidence of observations of boars in cities requires additional considerations, such as water availability during the dry seasons.

According to Ballari and Barrios-García (2013), variations in seasonal and geographical energy requirements and food availability determine food selection and the derived spatial behavior. Floral and faunal diversity in urban ecosystems reflects landscape heterogeneity (Alberti, 2005). Urban areas contain open spaces that vary in their "naturalness" from remnant native ecosystem patches to fully introduced and managed vegetation communities. Patch size, habitat heterogeneity and connectivity decrease towards the city center while patch density increases (Goddard et al., 2009). Studies of animal movement suggest that movement characteristics and patterns respond to the geographic environment, especially landscape connectivity. For example, construction of freeways and roads fragments natural ecosystems and has a significant impact on large mammals as they restrict dispersal and isolate individuals in small habitat fragments, and increase animal mortality from cars (Rudnick et al., 2012). Albano et al. (2012) used cameras to trace large mammals in the eastern Santa Monica Mountains in southern California. They found that wildlife movement between habitats was through suburban fringe and built areas, crossing various types of urban landscapes. Each type of landscape creates a certain level of resistance to movement, and animals tend to choose the easiest point of access to penetrate the urban fabric.

Wild boars exhibit various patterns of movement. While typically wild boars movement rate is 2-5 km/h, they are capable of travelling relatively fast over open ground, reaching speeds of up to 40 km/h. Moreover, they can tackle various obstacles. Larger wild boars can jump over barriers of up to 1.5 m, or traverse water bodies up to 9 km across (Baskin & Danell, 2003).

Wild boars spend a large portion of their daily activity budget (40–70%) on foraging (Blasetti et al., 1988). They are gregarious animals with social hierarchy governing their spatial behavior. They form sounders of 5-20 individuals dependent on reproductive activities (Oliver & Leus, 2008). They communicate using scent, sounds and visual cues. In what follows, we assume that availability of food may cause wild boars to leave their habitat and enter the built area.

Within urban areas wild boars show increase in nocturnal activity duration and movement distance due to patchy landscape and disturbance avoidance (Podgórski et al., 2013). Their foraging movement characteristics exhibit seasonal changes with variation in food availability (Massei et al., 1996).

3. Wild boars in Haifa

Haifa is the third largest city in Israel with a population of 270 thousands and metropolitan area of more than a million people (CBS, 2009). It covers 65.2 km^2 (Haifa municipality, 2008) on Mount Carmel, on the Eastern coast of the Mediterranean Sea (Figure 1), extending from sea level to an elevation of approximately 450m.

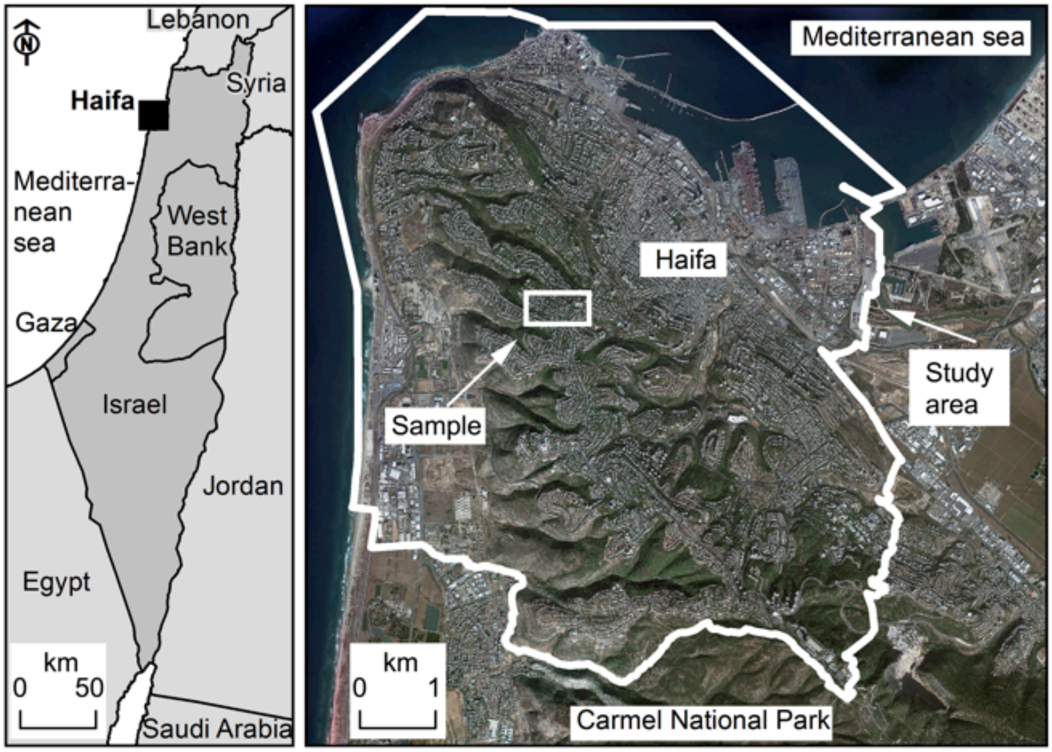


Figure 1: Haifa area with the location of the sample research area (marked square). See details of the Sample areas in Figure 4b below

The city's pattern is a complex mosaic of various building types, intertwined with vegetated ravines (wadis). It is bounded by the Carmel National Park to the south.. The semi-natural open space land-cover in Haifa consists mostly of rocky slopes with varying aspects, covered with Mediterranean scrubland and woodland, and patches of grass. It consists of oak, pine and carob vegetation communities, remnants of semi-natural forests, as well as planted pine trees following afforestation projects. Within the city boundaries various wildlife species are found, including badger (*Meles meles*), fox (*Vulpes vulpes*), wild boar (*Sus scrofa*) and jackal (*Canis aureus*), mongoose (*Herpestes ichneumon*), rock hyrax (*Procavia capensis*), porcupine (*Hystrix indica*), and others.

This work builds upon previous studies of open spaces in Haifa (Toger et al., 2015; Czamanski et al., 2014). These studies revealed that besides the decrease in total amount and increasing fragmentation of open space in Haifa, many open-space patches remain and their network is still rich in connections. Corridors that can be traversed by boars were identified in Haifa, suggesting that wild animals can penetrate the built areas.

In recent years the presence of wild boars became an increasingly significant issue in Haifa. During the night search for food wild boars penetrate from the open spaces to the outskirts of the city's built areas and then deeper into the inner neighborhoods. Some Haifa residents view this as an opportunity to interact with nature and wildlife within the city boundaries, while others see this as a nuisance (Barshaw, 2012). Haifa municipality systematically records observations reported by citizens. We compiled the reported full data for years 2011 – 2013 and partial data for 2010 and 2014. The reports suggest that over time wild boars are penetrating deeper into the city's neighborhoods (Figure 2).

The number of calls to the dispatch increased from 1194 in 2011 to 2002 calls per year in 2013. We analyzed distribution of distances from the observation points to the nearest large open-space patches (areas of at least 3ha), and their change over time. Figure 2d illustrates that the boars penetrate regularly into the city at distances of up to 400 m. The mean observation distance decreased due to higher frequency of boars near the greenspaces. The 99th percentile distance, however, that is more indicative of the long-distance movements, increased dramatically over time from 224m during 2011 to 333m during 2014. The deeper penetration distances, coupled with the growing number of observations reported to the municipality, suggest that this is an issue of increasing concern in Haifa.

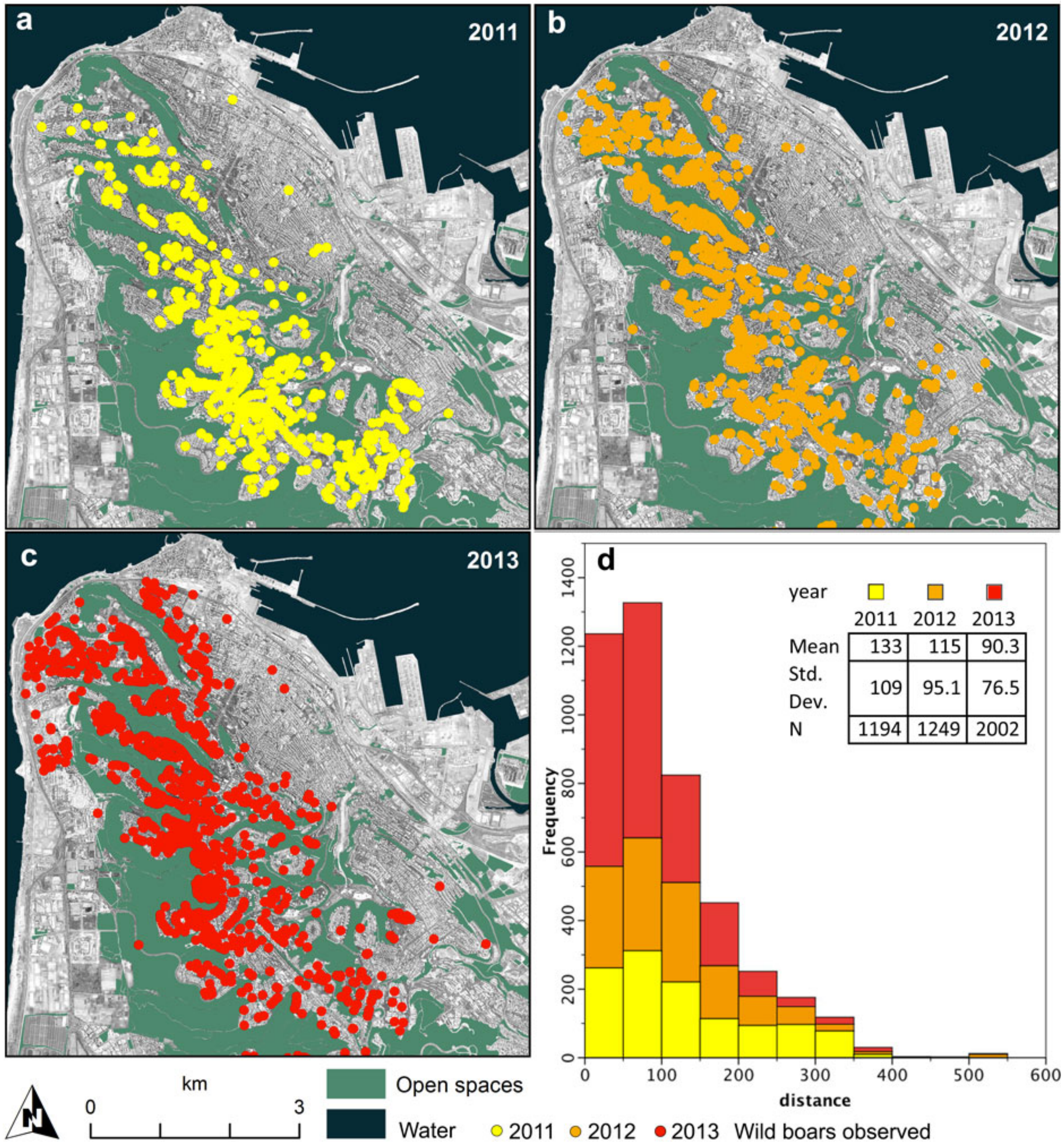


Figure 2: Wild boar sightings recorded by Haifa municipality, for the years 2011-2013 (a-c) and the distribution of penetration distances (d).

4. Methods: An agent-based model of wild boar foraging in Haifa

The purpose of our simulation model is to examine the influence of the presence of food sources in urban areas as a pulling force and of human presence as a repulsive force on the penetration of boars into cities. The presence of humans is formalized as a cost of moving through urban space. By incorporating these juxtaposed forces we identify values of parameters that make the city an attractive alternative to foraging in natural areas and investigate the depth of boars' penetration into the city. In our simulations we account for possible competition for food, albeit under restricted conditions. While we cannot distinguish the effect of the landscape configuration on animal movement from the impact of the foraging strategy (O'Sullivan & Perry, 2013, p134), we search for repeated patterns in spatially restricted attraction-repulsion cityscapes.

Our model simulates nightly foraging movements of wild boars across the urban areas. Based on empirical literature, we assume that wild boars possess high olfactory and cognitive abilities and detect food resources at a considerable distance (Kornum and Knudsen, 2011). In the current version of our model we assume that boars' perception and environment do not change as a result of increased tameness and postpone the explicit study of boars' ability to memorize and repeat the paths between food sources. Instead, we assume that the boars are able to take a close to optimal path between the food sources. In reality these paths cannot be established without multiple trials and errors and the species should be able to repeat them in consecutive days based on the memory, scent marks or both. The model focuses on boars' choice of most attractive food sources and movement between these sources. The simulation is implemented in the NetLogo modeling environment (Wilenski, 1999).

4.1 Model overview

Empirical observations (Figure 2) and expert opinions point to significant presence of wild boars in Haifa's open spaces that are rich in shrubby vegetation and provide ample shelter to animals. Our agent-based model simulates "*boars*" that are located within open spaces at the boundary of the city's built area at dusk, penetrate from there into the built-up areas to reach food sources (henceforth "*snacks*") moving among food sources distributed in the built-up areas and return to the open spaces at dawn to hide and rest during the day. Each boar-agent can be treated as a sounder of females with offspring or as a solitary male. The simulation night lasts 10 hours and proceeds by *ticks* τ of 1 min. Thus, each simulation run describes boars' foraging during 600 ticks. The time during which boars do not forage is ignored. We assume that boars are goal-oriented, aiming to maximize their food intake at a minimal cost. At each *tick* every *boar* takes an action that is dependent on its *state* (Figure 3).

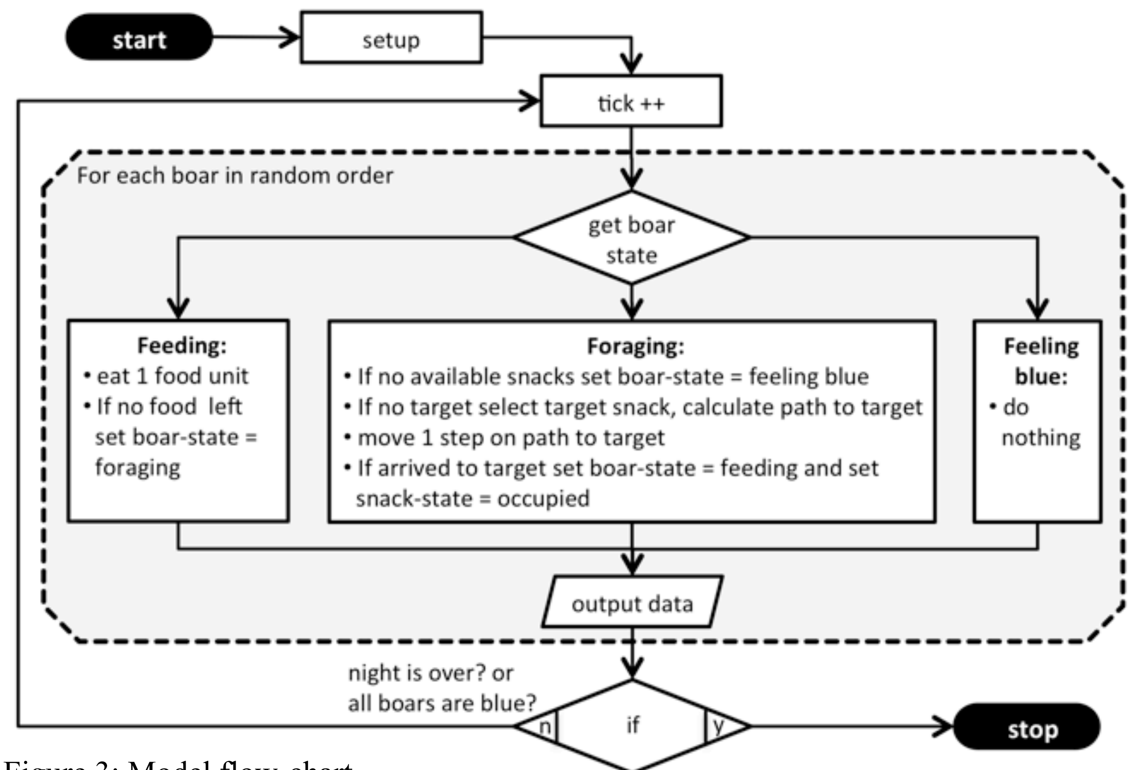


Figure 3: Model flow-chart

The possible states of each boar comprise *feeding*, *foraging* and "feeling *blue*". *Feeding* state: the boar is at the snack, decreasing food amount by 1 unit/tick. *Foraging* state includes selection of target snack, calculation of the path and movement towards the target by 1 cell/tick. A boar enters the *blue* state when no available snacks are found; it stops in place. The model run stops when the night is over or when all boars are *blue*. See appendix for details on the *Feeding* and *Foraging* sub models.

4.2 Boars-Food interaction

Boars are attracted to snacks. When boars arrive at a snack, they occupy the site, making it inaccessible to other agents. Boars feed consuming 1 unit of food per 1-minute tick. They feed until the snack is depleted and no food remains at the site.

The wild boars are intelligent animals with keen senses of smell and hearing. By means of scent and sound they are aware whether another animal occupies the site. Boars do not share food sources. If a boar occupies a site, other boars are unable to join the feeding and have to search for other snacks.

In this model, the *boars* detect *snacks* from a distance by smell. The intensity of the scent of a snack depends on the amount of food at the site and on the distance between the boar and the food source. The agents estimate snack *attractiveness* using exponential distance decay function $A(d) = A_0 \exp(-\alpha d)$, where d is the Euclidian distance from the boar's current location to the snack, A_0 is the amount of food at the snack and α is the decay rate of smell. In what follows, the scaling coefficient α is adjusted in a way that the smell decreases 10 times every 25 m from the snack. Attractiveness is set to zero when the distance d is above a threshold d_{max}. In what follows d_{max} = 250 m the distance at which the smell of a snack is practically zero.

The boar smells all snacks at a distance below d_{max} and selects the snack i of maximal attractiveness. Then the least-cost-path to this snack is calculated. We estimate the least cost paths with the A-star least-cost path algorithm, assuming that the neighbors of a given patch are those within a standard Moore 3x3 neighborhood. In case the average cost of this path is below γ the boar starts moving to the best snack. If the average cost of the least cost path to the best snack is above γ, then the next best snack is selected until the snack with the average cost below γ is found.

4.3 Boars-Landscape interaction

The urban landscape is rich in resources (food and water) as well as dangers and disturbances for wildlife. A foraging animal in a patchy landscape optimizes energy gain from food intake versus the cost/risk of movement (Charnov, 1976). Moreover, the movement paths are less sinuous in a high-risk environment (Fahrig, 2007). As stated above, in the current model we assume that urban landscape is a high-risk environment known to the boars from previous foraging and thus the *boars*' movement follows shortest (least-cost) paths. The least-cost path is determined over a resistance (*cost*) surface derived from land-use/land-cover (LULC) data (see section 4.4). The landscape comprises 5x5 m square cells (*patches*) each with *cost* attribute that represents perceived risk of movement across the cell due to disturbance (e.g. crossing roads).

For the wild boar species, the disturbance avoidance is linked to their habituation to humans (Licoppe et al, 2013). In order to simulate boars' avoidance of dangerous environment we characterize boar's path between two food snacks by γ – average, per meter of length cost of this path. We further introduce γ-threshold and consider paths for which γ is below the threshold. Higher γ-threshold enables higher variety of path choices that is, less restricted movement through the landscape. The range of γ values is defined by the area land-uses/land-covers (see below).

4.4 The model space

The model area is characteristic of Haifa land-cover patterns. It includes parts of semi-natural vegetated open spaces (wadis), urban gardens and parks, backyards, buildings and roads. The space is a 500 by 1000 m rectangle and is represented in the model by 100x200 grid of 5x5 m cells (Figure 4). The 5m grain size is detailed enough to detect individual buildings and backyards. Cell's neighborhood is a 3x3 Moore neighborhood of 8 adjacent cells.

The sample input space was prepared based on the classification of 2012 aerial photograph into 20 LULC types (Toger et al., 2015). The vector polygons were rasterized based on the majority rule, into 5x5m cells. Classified aerial photos were used for establishing the "resistance to movement" - cost of crossing the *patch* (Table 1).

LULC	Description	cost	category
Forest	Semi-natural and planted forests and woodlands	0.001	Open Space
Shrubs	Mediterranean scrubland		
Grassland	Herbaceous vegetated areas		
Orchard	Vineyards and orchards	0.1	Transit
Garden	Managed vegetated areas: parks, gardens, lawns, etc.	0.25	
Wasteland	Garbage, dunes, beach, mines, wasteland		
Fallow	Abandoned and fallow fields		
Backyard	Backyards, squares, logistic spaces around buildings	0.5	
Field	Cultivated open areas		
Dirt road	Unpaved roads		
Foot path	Paved footpaths		
Trail	Unpaved foot paths and trails		
Transport	Railroads, parking, airports, sea ports	0.75	
Roads	Paved roads		
Buildings	Buildings	∞	Obstacles
Industry	Industrial areas, exurban commercial areas		
Construction	Construction sites		
Agri-built	Greenhouses, warehouses		
Water	Water		

Table 1: Land-use/land-cover (LULC) classification and cost per meter

Following (Rudnick et al., 2012), we consider cost as combined measure representing disturbance from human activities (perceived risk of movement) and energy expenditure of a boar (Spear et al., 2010) and establish the cost based on the Land-Use/Land-Cover (LULC) classification, in a way that is standard in connectivity analysis studies (Zeller et al., 2012). Specifically, for every LULC class, we established the cost of resistance based on the Naali's (2009) species-specific index of traverse-ability for land cover types for the porcupine: relative resistance values of 0.001/m for natural areas and olive groves, 0.1/m for orchards and 0.25/m for fallow crops areas. We accept porcupine's values for boars and further assume that for a boar the cost of crossing a backyard is 0.5/m, twice as hard as crossing a fallow agricultural field, while crossing a road costs 0.75/m. While the cost values could be argued, the main parameter that affects the movement paths is the average animal’s sensitivity to disturbance γ.

4.5 Formalization of boars' movement

After a boar selects a target snack *i*, the least-cost path between the boar's current location and snack *i* and the average cost of traversing a cell along the path are calculated. If the average path cost per cell is higher than the threshold value γ the path is excluded from consideration. We consider this approach as a simplified interpretation of a memory-based trial and error process outcome. Namely, if the per-cell cost of traversing γ is too high then the path contains either an essential number of almost impassable cells or many cells that are actively avoided by the boar. We assume that the boar "accumulates" the cost when traversing the path and in both cases will fail to follow the path and turn back.

On the way to a selected snack, at each cell, the boar may reevaluate the attractiveness of targets that it can smell and decide to move to a different target. Below, we apply the probability of re-evaluation $p_{reevaluaiton} = 0.1$. When reevaluating, the boar considers all snacks with attractiveness equal or higher than the current target and selects a new target.

4.6 Model initialization

In what follows we compare patterns of boars' movement in an abstract, "garden" landscape" (Figure 4a), and in real Haifa landscape, the white rectangle in Figure 1 (Figure 4b). In garden landscape the cost of each cell is set to characteristic of gardens value of 0.25/m.

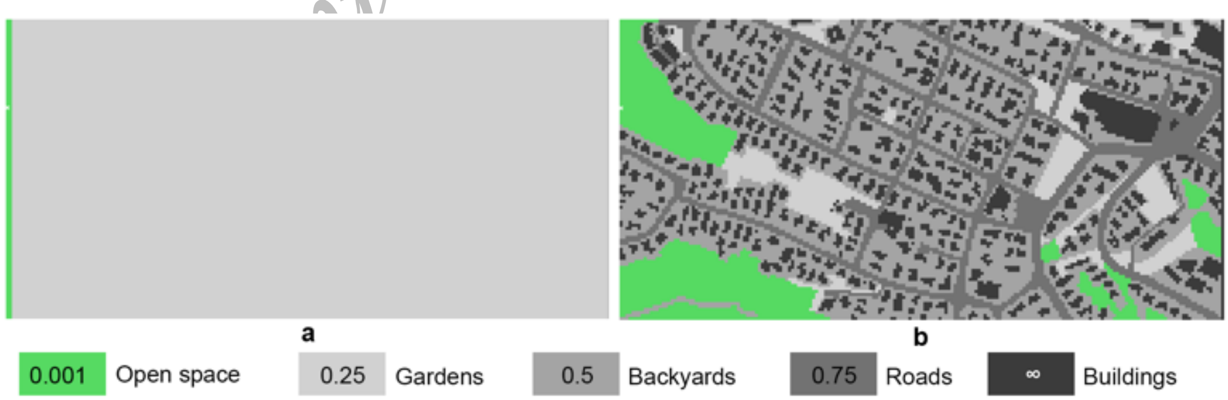


Figure 4: (a) Garden and (b) Haifa landscape scenarios.

In the garden landscape, N_{snacks} *snacks* are randomly distributed over the entire area. In case of Haifa landscape, snacks are always located in cells with "backyard" LULC and all backyard locations are considered equally probable. Snack represents human-generated source of food such as garbage bins, cat feeding points, compost points, fruit and seeds from garden plants, and irrigated yards.

Each food source initially contains $A_0 = 60$ units of food for hourly feeding. In simulations runs, we vary boar population size and number of snacks (N_{snacks}). Preliminary analysis demonstrated that within the reasonable range of boar numbers (5 - 25 boars) model dynamics is defined by number of snacks per boar (*SPB*). The experiments we describe here were based on populations of 10 boars and SPB values between 2 and 20. All results below are averaged over 10 simulations with the same parameter values.

Boars start at the boundary between the open space (cost = 0.001) and urban area. We investigated the model for two initial distributions of boars: all starting in the common initial location and randomly spread along the border. The results are qualitatively similar and, for simplicity, we present below the results for the common initial location.

4.7 General view of the boars' penetration into the city

Figure 5 presents maps of boars' locations and paths at the end of the night, $\tau = 600$, for the *SPB* = 5 for the garden (Figure 5a) and Haifa (Figures 5b, 5c) landscapes

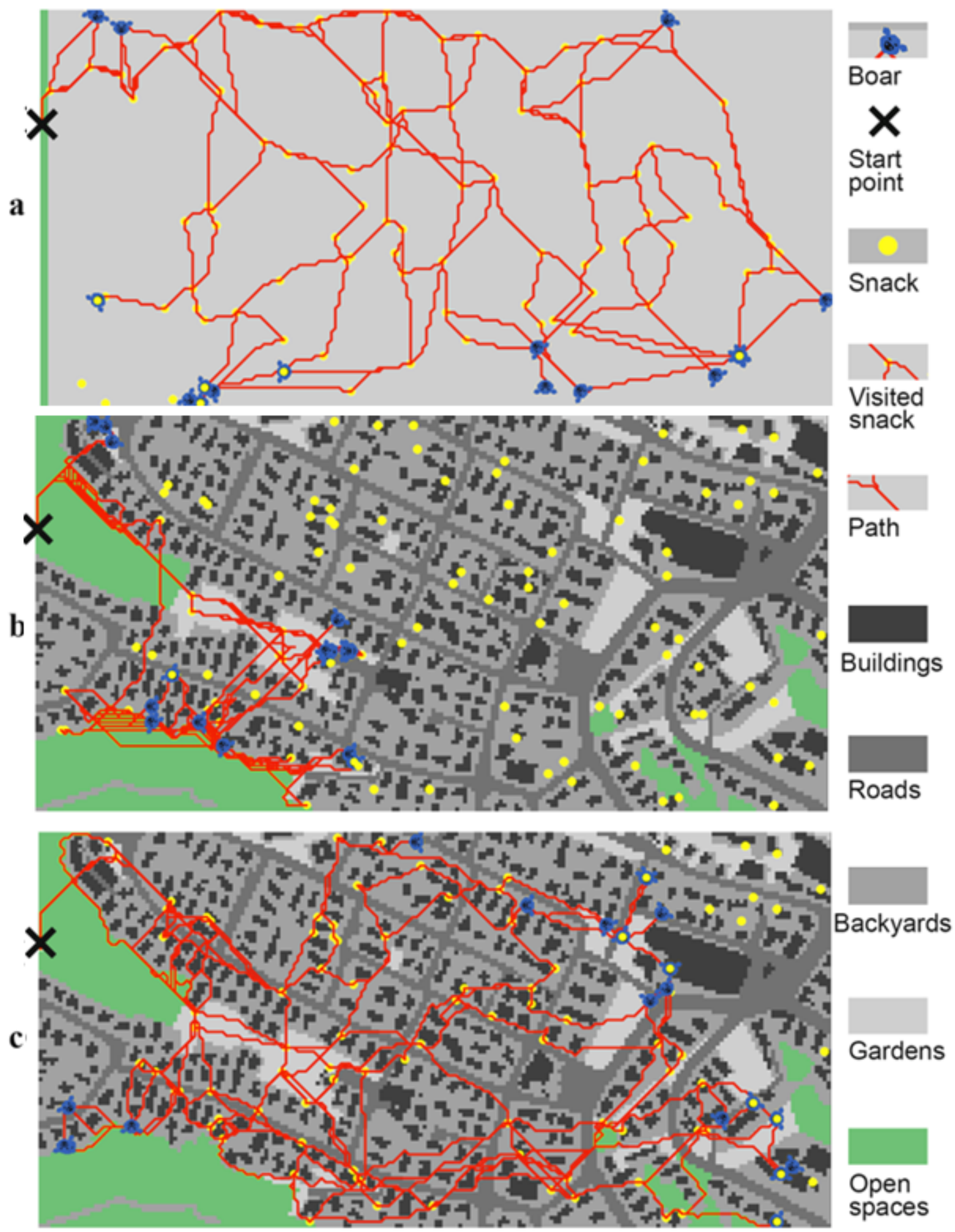


Figure 5: Simulation results for SPB = 5, (a) Garden landscape, $\gamma = 0.3$/m (b) Haifa, $\gamma = 0.3$/m, (c) Haifa, $\gamma = 0.6$/m

As can be expected, in the homogeneous garden landscape, boars' locations during the night form a front that moves ahead, towards the distant boundary of investigated area (Figure 5a). In heterogeneous Haifa landscape, in case of relatively low number of snacks and low γ, the average cost γ of *any* path between most of the snack pairs is above the threshold. Under these circumstances, boars do not get far away from the natural areas at the city boundary (Figure 5b). The situation changes if γ is set to be higher, as for γ = 0.6/m (Figure 5c). In this case, boars penetrate Haifa just as far as the garden landscape (where γ = 0.3/m) (Figure 5a).

In what follows, we calculate a depth of penetration as the furthest X-axes projection of the boar night trajectory. We describe the model dynamics by dependencies of penetration distance on snacks per boar ratio (SPB) and γ. All results below were averaged over 10 model runs and over 10 boars.

5. Simulation results

5.1 Low traverse threshold γ

We first consider penetration distance for the garden landscape with the traverse threshold γ = 0.3/m that is only slightly higher than the cost of the homogeneous garden landscape (0.25/m) and penetration distance for the heterogeneous Haifa landscape (Figure 6).

a

b

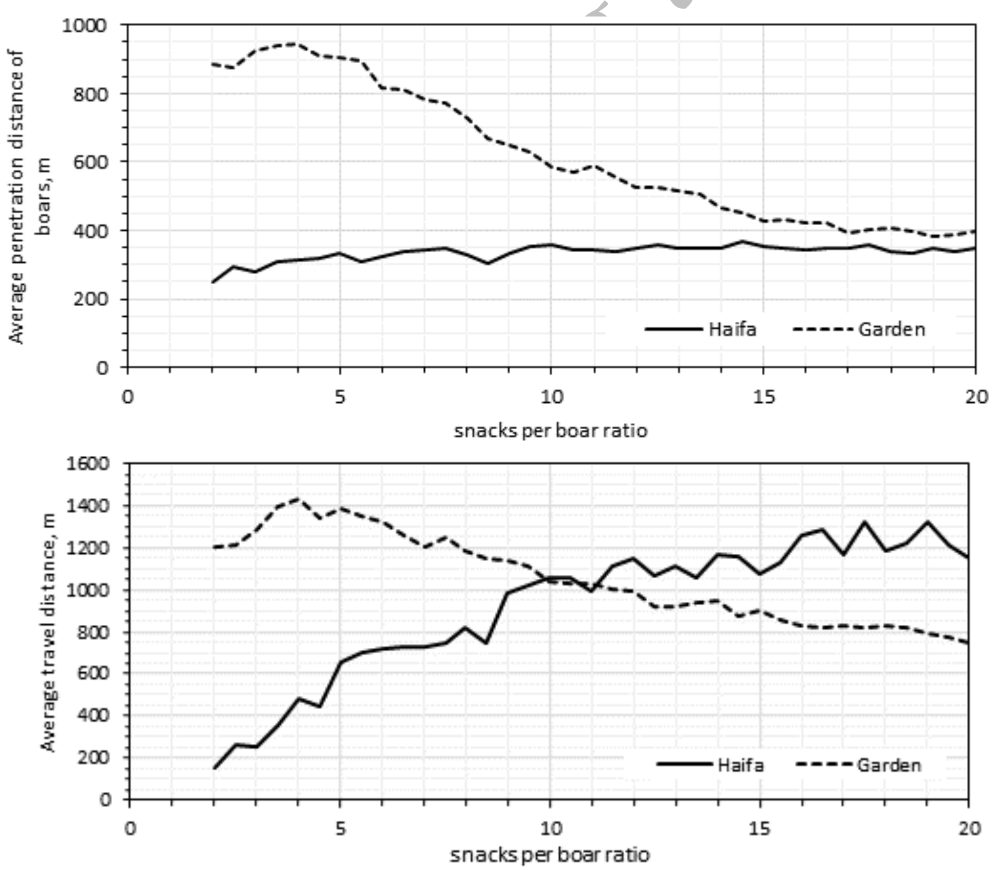


Figure 6: Penetration distance (a) and total traveled distance (b) of boars in Haifa and uniform scenarios, 10 boars 600 ticks varying snacks number, γ = 0.3/m.

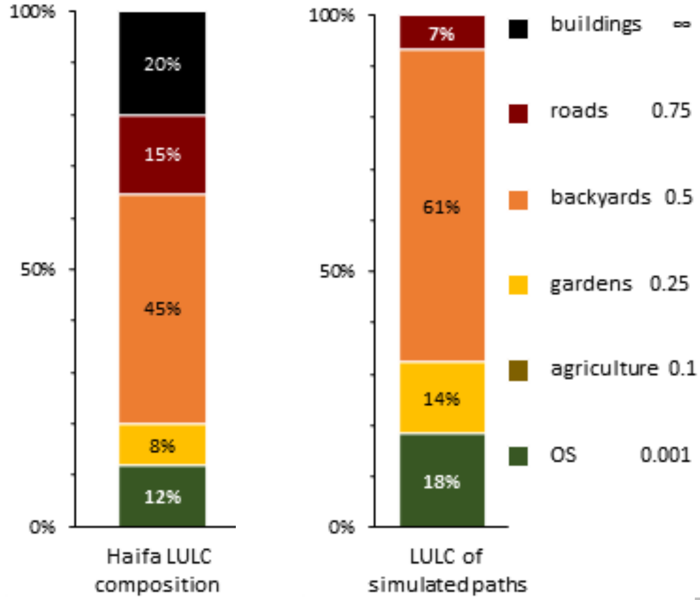
In the homogeneous "garden landscape" the penetration distance remains high up to the value of SPB ~ 5. As is to be expected, for the higher value of SPB this distance decreases (Figure 6a). Indeed, with the increase of SPB, the distance between the snacks decreases and the area that the boar covers for collecting the same amount of food decreases too. In the homogeneous environment (garden) this decrease results in a decrease of the penetration distance.

The dependence is qualitatively different for the Haifa case. If $\gamma = 0.3$/m and low SPB (high distances between snacks), the majority of the least cost paths cannot circumvent relatively costly parts of urban area - backyards and roads. As a result, the value of γ for these paths is above 0.3 and the boars are locked within the neighborhoods of the open spaces and gardens. With the increase in SPB the importance of γ threshold decreases and the penetration distance into Haifa increases. Numerically, the difference between penetration distance for the garden and Haifa scenarios remains four-fold for the value of SPB below 5 and then gradually decreases reaching 10% of the level characteristic of a uniform garden landscape at SPB ~ 15. As should be expected, penetration distance for the homogeneous garden landscape always remains higher than for the heterogeneous Haifa scenario. The dependence of the average travel distance on SPB (Figure 6b) supports these arguments.

The above results for Haifa clearly manifest the influence of urban heterogeneity on the boars' penetration into the city. If boars' abilities to traverse urban areas were low, then they would remain at the periphery of the city and would not enter the inner neighborhoods.

The observations (Figure 2) show that boars systematically penetrate up to 400 m into the built areas of Haifa. We consider this as an argument in favor of the traverse threshold being higher than that of the garden landscape. Therefore we are looking for the traverse threshold cost value γ such that Haifa inner city becomes accessible for the boars.

The influence of the traverse threshold on the model outcome is not obvious because it is defined by LULC composition along the cheapest paths between snacks. Land composition along these paths (Figure 7b) is different from the LULC composition of Haifa landscape (Figure 7a). Note that the cheapest paths between snacks follow available open spaces and gardens and contain half the percentage of roads (Figure 7b).



a **b**

Figure 7: LULC composition in (a) Haifa landscape and (b) along the boars' paths.

5.2 Varying traverse threshold γ

To examine the ability of boars to penetrate deep into Haifa's built areas, we investigate the dependencies of average penetration and movement distance in Haifa on traverse threshold γ (Figure 8).

a

b

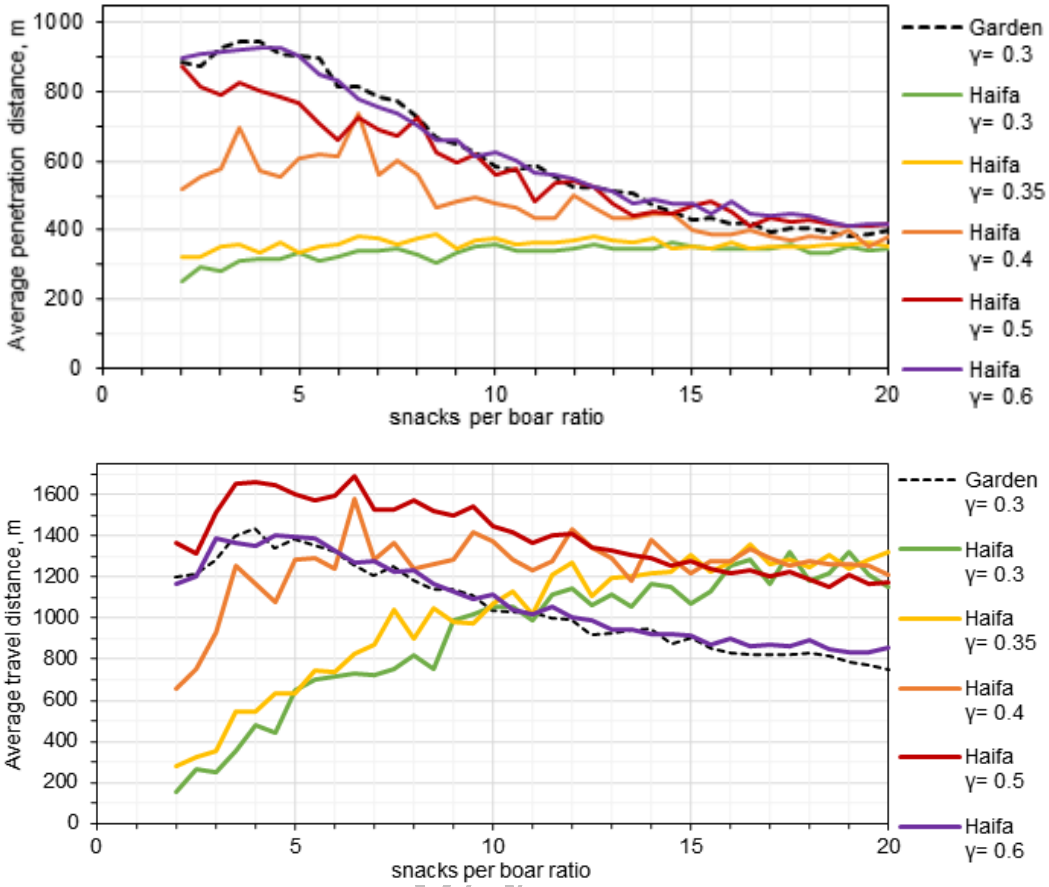


Figure 8: (a) Average, penetration distance and (b) total travel distance of boars for the Haifa scenario and traverse threshold γ between 0.3 and 0.6 and for the garden scenario (that does not depend on γ) for γ > 0.3/m.

As can be seen in Figure 8, for the values of γ below 0.4/m the city is impenetrable for the boars despite monotonous increase in the distance traversed during the night, they cannot go too far inside the city no matter how dense is the food pattern. As far as the value of γ exceeds 0.4/m, the landscape becomes "porous" for the boars – the average travel distance quickly grows with the growth of the SPB and is higher than city width (1 km) when SPB is above 3 (Figure 8b). Low SPB values cause deeper penetration of boars into the city in search of the food (Figure 8a). Higher SPB make distance penetration unnecessary – the boars become able to forage over the part of the city only during the entire night (Figure 8a). The increase of γ to 0.5/m increases average travel distance to maximal possible. Very high - close to 0.6/m and higher, values of γ make Haifa penetrable just as the homogeneous garden pattern (Figure 8).

The critical values of γ – 0.4/m, 0.5/m and 0.6/m are defined by the LULC ratios along the least cost paths in the heterogeneous Haifa environment (Figure 9).

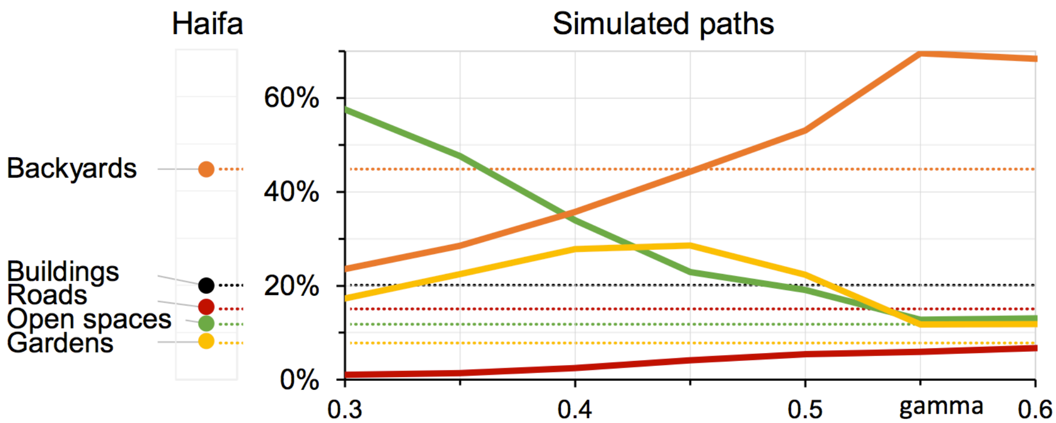


Figure 9: LULC composition of simulated boars' paths as dependent on γ.

Indeed, according to Figure 9, for the value of γ below 0.4/m, the fraction of the backyards, where the food snacks are located, along the least cost paths is lower than the fraction of the open spaces. In these circumstances, the boars' movement is often contained within the isolated patches created in the areas with high fraction of the open space. When γ exceeds the value of 0.5/m that is characteristic of the backyards, roads only become meaningful obstacles for the boars. Further on, γ > 0.6/m is sufficient for crossing the roads along the least-cost path between any two locations in Haifa. That is the entire Haifa urban space becomes porous as the garden landscape. Moreover, Haifa's wadis that enter deep into the city (Figure 2) create these pathways that bring pigs close to the food sources.

6. Discussion and Conclusions

The amount of food availability in Haifa is very high. There is a garbage bin near every building. In addition there are cat-feeding points and unofficial boar-feeding locations. Further, during the dry seasons of the year irrigated water is available in the back yards, an important resource for the boars during these periods of the year. The observations of boars in Haifa indicate that over time wild boars are penetrating deeper into the built areas of the city. There are several reasons for this phenomenon - an increase of the boar population, growing abundance and attractiveness of food sources in the city and decrease in animals' sensitiveness to human presence (Luniak 2004).

Our study confirms that the city's heterogeneous landscape may be porous to wildlife. Humans' view of the city is intuitively distracted by the numerous landmarks and borders (e.g. buildings, roads, fences) that are dangerous or impossible for boars' traversing. However, the heterogeneity of the Haifa land-cover is sufficient for going around these lands and developing routes between the points of food supply that are much easier to traverse. According to our simulations, since the boars are able to move through the backyards and other less deterring urban areas, the city becomes fully penetrable for them. In such a porous city, the distance of boars' penetration is defined by the relative availability of food – the SPB ratio. Given the fixed area of the model application, we can generalize this ratio for the arbitrarily area as Snacks-per-Boar-per-Area. The dependence of the penetration distance on the SPB is non-linear and defined by the total travel distance that the boars have to cover during the night to accumulate the required amount of food. For the Haifa conditions, in case of the low SPB some of the boars cannot find the next snack to feed after exploiting the current one. As a result, they may cover the entire city searching for food and still need more, given that the resistance values are low enough. As far as the SPB ratio surpasses the threshold, which is Haifa case is about SPB = 5, the necessary amount of food can be accumulated over the area of lower size and the depth of penetration is decreasing with the growth of the SPB. The behavior of boars in Haifa satisfies both conditions. Namely, the animals are tolerant enough to human presence to freely cross the backyards and land-cover and the food supply in the city is far above SPB = 5.

Our current research is focused on specific urban morphology and boars' presence in Haifa. . Other areas in Haifa have more roads and buildings, some can have more gardens and open spaces. Certainly this is the case in other cities. To extrapolate models results, we propose γ, a universal index of penetrability of the area for the boars or any large animals that observe urban landscape at human resolution. It is the average cost γ of crossing land cells along paths connecting pairs of the feeding points. The value of γ is defined by the range of the resistance values as chosen to characterize the LULC types and by *two spatial patterns* - one of the land types and the other of the food sources. The same ratio of the LULC types may result in very different spatial land patterns and, further, different patterns of the food sources superimposed on the LULC pattern may result in either easy path from one food source to another, or, in opposite, demand crossing dangerous and highly resistant patches on most of the paths. The value of γ is estimated based on the LULC pattern and the pattern of the food sources for each path between pair of the food sources. The model dynamics is defined by this intuitive index – when γ is low for the species, animals remain within the areas of relatively low resistance. When γ is high, the system dynamics is defined by the spatial distribution of food in the city.

Representation of food sources as a set of mangers each replenished anew every day limits non-urban applications of our model. Natural sources of food are much less concentrated, have their own time dynamics and are restored gradually. That is, natural food sources cannot be considered as a simple network that is implemented in our model.

Our model assumes that the boars can identify the least cost path between the food sources. In reality these paths cannot be established without multiple trials and errors and the species should be able to repeat them the other day based on the memory, scent marks or both. Empirical studies of wild boar movement indeed suggest that foraging behavior incorporates memory-related exploration of territory together with returning to known food locations. In experiments, the combination of faithfulness to certain areas with rare sallies over larger ranges, in accordance to the Lévy flight foraging hypothesis (Vishwanathan et al., 2008) is observed. These researchers enforce incorporation of boars' ability to memorize the path into the model and explore, in this way, the emergence of the paths between the food sources in the city. Memory-based assumptions are essential for our model too: the use of the least-cost path demands familiarity with the landscape and some memorizing of the daily trials and errors or reaction to the previous smell marks. In this study we avoided memory-related modeling of the landscape exploration and focused analysis of penetration assuming that the landscape has already been explored, and the costs and least-cost paths are known.

Data collected in Haifa since 2010 indicate the extent of wild boars' penetration into urban areas. The phenomenon increasingly becomes a nuisance and now Haifa policy makers seek ways to minimize the damages from wild boar overabundance and reduce human-wildlife interactions. Haifa is not unique in this respect and the penetration of wild boars into urban areas causes concerns for wildlife management agencies and municipalities around the world. There are attempts to decrease boar penetration into the urban areas by decreasing wild boar abundance in the peri-urban area, altering distribution of the urban food or increasing landscape resistance to boars' movement. This is a very recent problem of urban policy in Haifa, and, currently, public opposition to boars' population control by culling or sterilization motivates the search for alternative policies results in appeals for boar-proofing garbage bins or fencing areas against boar penetration (JPost.com 2007) and educational campaign against intentional feeding (Yaron 2014). The benefits of alternative political decisions, such as reduction in boar population or boar-proof bins, in relation to their cost yet should be done in regards to the dynamics of entire system as represented in the model.

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Appendix A. Sub-models of Feeding and Foraging including target choice

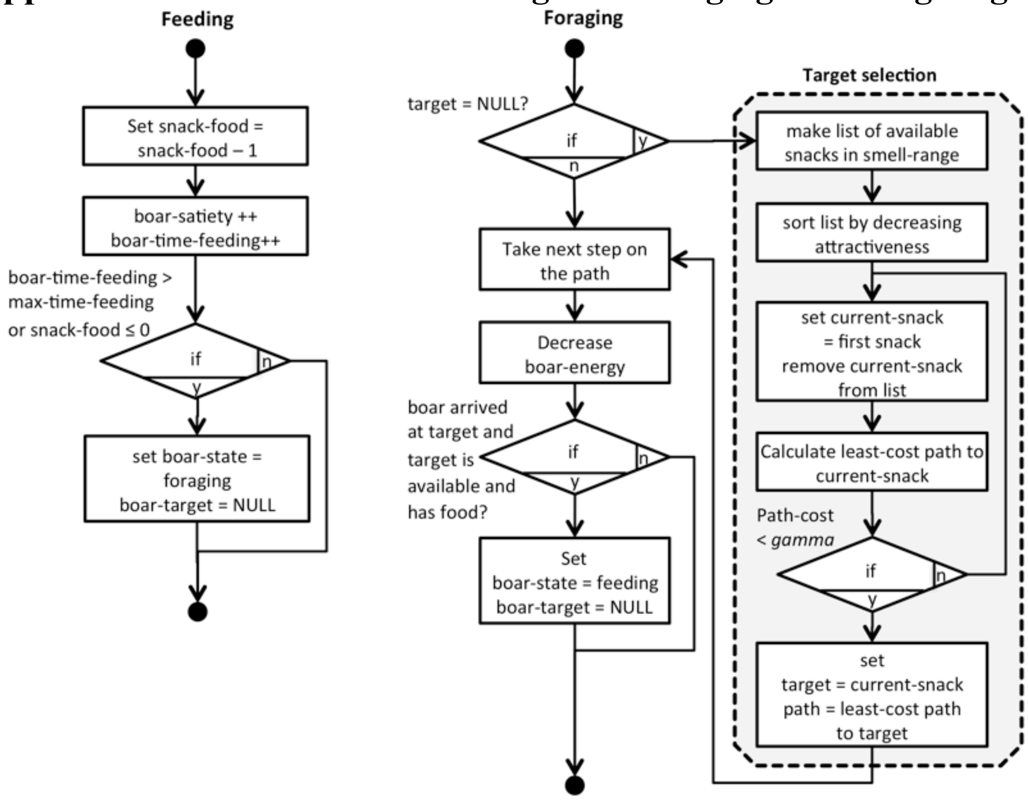

Figure A1: The flow charts of Feeding and Foraging sub models