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Utilizing a cellular automaton model to explore the influence of coastal flood adaptation strategies on Helsinki's urbanization patterns

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ABSTRACT

A cellular automaton model (SLEUTH-3r) is utilized to explore the impacts of coastal flood risk management strategies on the urbanization parameters of Helsinki's metropolitan area, at a 50-m spatial resolution by 2040. The current urbanization trend is characterized by the consolidation of existing built-up land and loss of interspersed green spaces, whereas the most intense growth is forecast inside the coastal flood risk areas. This baseline is compared to strategies that test various responses of the planning system to real estate market forces and the spatial distribution of flood risks. A set of scenarios translates property price effects of flood risk information into various attraction-repulsion areas in and adjacent to the floodplain, while a second set explores varying degrees of restricting new growth in the flood risk zones without reference to the housing market.

The simulations indicate that growth under all scenarios is distributed in a more fragmented manner relative to the baseline, which can be interpreted favorably regarding house prices and increased access to ecosystem services, although the indirect effects should also be considered. Demand for coastal flood-safe properties does not appear to automatically translate to refocusing of development toward those areas, unless planning interventions encourage this redistribution. The character of the planning system with respect to market drivers and the spatial distribution of risks and amenities is thus important. A mixture of market-based measures and moderate zoning interventions may be preferable for flood risk management and provide the necessary precision for adaptation strategies.

1. Introduction

Coastal urbanization is typically characterized by intense concentrations of population, infrastructure, and activities. Proximity to the sea and coastal ecosystems entails risks, notably flooding; however, it also drives growth in coastal urban agglomerations. The question is, therefore, how to steer coastal development toward sustainable configurations: risk management and adaptation to changing risks require not only flood-related restrictions, but also understanding how spatial interventions affect fundamental mechanisms behind urban growth and development.

However, it is often assumed that risks and interventions interact in the absence of urban dynamics. One reason is the uncertainty surrounding urbanization. Evidence-based modelling frameworks are rare and the absence of quantified scenarios prevents urban evolution from being grasped or accounted for during decision-making. Moreover, it is often neglected that decision-makers seek clear signals from markets, which, however, react to immediate changes rather than to gradual phenomena such as urban evolution. Loose connection of urban dynamics with flood-related interventions may entail conflicts between environmental and economic objectives that hinder urban sustainability; for instance, municipalities often reconcile strict land use policies with pragmatic growth targets. Consequently, there is substantial need to implement assessment frameworks that quantify the link between urban dynamics, climate-sensitive risks, and interventions. The use of cellular automata is motivated by their ability to model the evolution of the adapting city concurrently with the impacts of spatial interventions and to reproduce the distribution of growth in a spatially explicit manner, allowing to understand the implications of alternative spatial policies and refine them.

This study aims to explore the influence of flood-related policy instruments on urbanization dynamics, by calibrating the SLEUTH cellular automaton model for Helsinki's metropolitan area and simulating three scenarios. The first scenario forecasts the evolution of Helsinki's current urbanization trends as identified in calibration. The second (with two variations) simulates a market-led adaptation process that relies on flood risk information and subsequent price and demand adjustments in the housing market. The third (with three variations) simulates an adaptation process that relies on regulating coastal growth without

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reference to market behavior. The simulations offer insights into how planning systems can respond to flood risks and to markets adapting to those risks.

2. Flood risk management and urban dynamics

Coastal and river-line areas are the most vulnerable to climate-related impacts (Wilbanks et al., 2007). Flooding is a major risk in urban areas (Revi et al., 2014) and the economic losses of coastal flooding are expected to rise, owing to unsound urban development and exacerbated by changing hydrological patterns and sea levels (Nicholls & Cazenave, 2010; Neumann et al., 2015; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, & Feyen, 2017; for Helsinki, Venäläinen et al., 2010; Parjanne & Huokuna, 2014; for Finland, Perrels et al., 2010). It has been recognized that resilience to flooding requires a comprehensive understanding of the functioning of urban areas and of indirect effects mechanisms, beyond direct short-term damage costs (Aerts et al., 2014; Hallegatte, 2008; Li, Crawford-Brown, Syddall, & Guan, 2013; Meyer et al., 2013; Ruth & Coelho, 2007). Urbanization parameters affect all risk components (exposure, vulnerability, hazard severity; IPCC, 2014), whereas adaptation and sustainability objectives overlap through their interactions in society, industry, and the built environment (Wilbanks et al., 2007).

In practice, flooding participates in urban growth and development mechanisms in a number of ways. Flood risk is a locational disamenity that, if transparent, reduces house prices (Bin, Crawford, Kruse, & Landry, 2008; Daniel, Florax, & Rietveld, 2009), whereas disclosure of previously non-transparent flood risks adjusts prices according to risk (Votsis & Perrels, 2016) and income level (Rajapaksaa, Wilson, Hoang, Lee, & Managi, 2017). These effects can be bounded-rational (Daniel et al., 2009; Votsis & Perrels, 2016) and fade with time (Atreya, Ferreira, & Kriesel, 2013), but show that the spatial distribution of risks influences, via residential location and property price dynamics, aspects of a city's spatial equilibrium, notably land use and where new growth is demanded. Systematic non-marginal shifts have also been documented (Bin & Landry, 2013; Hallegatte, 2008), including when attitudes adapt to changing risks (Filatova, 2015; Filatova & Bin, 2013). For urban planning and management, policies representing different spatial configurations of risks, resources, and interventions entail different impacts from catastrophic flooding (Perrels et al., 2015), whereas well-functioning urban agglomerations have capital stock structures with long-term lower sensitivity to impacts (Perrels et al., 2010; Virta et al., 2011). Similarly, (over)production capacity in construction (Hallegatte, 2008), policies supporting accessibility and network flows (Li et al., 2013), and green infrastructure (Davies et al., 2011; De Groot, Wilson, & Boumans, 2002; Renaud, Sudmeier-Rieux, & Estrella, 2013) influence impacts and recovery, all posing their own implications for urbanization. Flood risks therefore both influence and are influenced by urban spatial dynamics, and the role of spatial planning interventions in steering urbanization to safer configurations is recognized (Neuvel & van den Brink, 2009; Schanze, Zeman, & Marsalek, 2006; Wilson, 2007). Spatially explicit modelling with cellular automata can explore the relation between natural and imposed land constraints, the transport network, and urban growth, and is increasingly used to forecast the future location and form of growth in flood-prone urbanities (Nigussie & Altunkaynak, 2017; Sekovski, Mancini, & Stecchi, 2015; Song, Fu, Gu, Deng, & Peng, 2017).

The shift of interest from flood protection to risk management and adaptation underlies Finnish strategies, bar spatial dynamical modelling. The metropolitan adaptation strategy, based on regional climate change scenarios, stipulates the consideration of extreme events and climate variation/change in land use planning (HSY, 2012) and a fine-grid assessment of social vulnerability to climate change has been produced (Kazmierczak, 2015). Detailed flood probability maps (environment.fi/floodmaps) are available in compliance with Finland's national climate adaptation strategy (Marttila et al., 2005) and EU's Water Directive (European Communities, 2000). These maps improved resilience in the real estate sector as prices/m^2 and demand adjusted to reflect more accurately the spatial distribution of coastal flood risks (Votsis & Perrels, 2016). More precise considerations of the effects of flood-related strategies on urban dynamics remain, however, unknown, both in international literature and in Finland. This study moves a step further by simulating the effects of information-led price adjustments and of alternative growth restrictions on urban evolution.

3. Methodology and scenario assumptions

3.1. Models

SLEUTH (**s**lope-**l**and-use-**e**xclusion-**u**rban-**t**ransportation-**h**illshade) is a cellular automaton model of urban growth and land use transitions (Clarke & Gaydos, 1998; Clarke, Gaydos, & Hoppen, 1997). This study implements SLEUTH-3r (Jantz, Goetz, Donato, & Claggett, 2010), a modification that maintains SLEUTH's functionality and theoretical underpinnings, but improves computational performance and introduces additional calibration metrics. Cellular automata (von Neumann, 1951; von Neumann & Burks, 1966; Batty, 1997, 2007) are computational frameworks that model in discrete time bottom-up interactions between elementary spatial entities (cells). They can both generate forms consistent with known urban processes and optimize those forms by simulating how different development strategies result in actual urbanization patterns (Batty, 1997). They consist of cells in an $n \times k$ lattice, initial and possible states of cells, and transition or cellular interaction rules that govern the state transitions of cells.

SLEUTH simulates four types of urban growth: diffusive, new spreading center, edge, and road-influenced. Diffusive (spontaneous) growth simulates urbanization non-contingent to preexisting infrastructure, while its expansion is simulated by new spreading center growth. Edge growth simulates urbanization contingent to existing urban areas, while road influenced growth simulates urbanization along major transport corridors. These growth types are controlled by five growth coefficients: diffusion, breed, spread, slope resistance, and road gravity. Diffusion (dispersion) controls a cell's random selection frequency for possible spontaneous growth. Breed controls the probability that a spontaneous urban cell will also become a new spreading center. Spread controls the probability that a new spreading center will generate additional urban areas. Slope resistance affects all growth types, controlling the extent to which urbanization overcomes steep topographies. Road gravity controls road influenced growth through the area of influence of transport infrastructure. Candau (2002) provides a full exposition. Gazulis and Clarke (2006) approach the growth coefficients as a region's DNA and illustrate how different combinations reproduce known urban morphologies. A calibrated model produces a scenario, if the calibrated parameters are used to forecast the future trajectory of observed growth.

SLEUTH is widely utilized (Chaudhuri & Clarke, 2013; Gazulis & Clarke, 2006) due to its transferability, straightforward implementation, computational efficiency, interpretability, and universalizability (Clarke, 2008; Jantz, Goetz, & Shelley, 2004; Silva & Clarke, 2002). The limitations of modelling urban dynamics via non-customizable transition rules rather than implementation of urban economic theory are a concern (Kim & Batty, 2011). However, the model's value is its high spatial resolution, standardized and accessible inputs (cf. the data needed by CGE or LUTI models), and first-principles approach that adapts a transparent set of spatial interaction assumptions into empirical settings. SLEUTH does not impose strong assumptions, accommodating diverse policy viewpoints.

3.2. Data

SLEUTH-3r is calibrated to capture Helsinki's growth dynamics at a 50-m spatial resolution. The full extent of Helsinki's metropolitan area is modelled, as in prior implementations (Caglioni, Pelizzoni, & Rabino, 2006; Iltanen, 2008). Urban growth depends on wider regional, national, and international flows; it is assumed that the chosen extent captures adequately the region's growth, since its spatial behavior is fairly self-contained. The calibration uses data from 2000 to 2012 as SLEUTH performs better when calibrated on short historical timeframes (Candau, 2002; Clarke, 2008). Fig. 1 displays observed growth during 2000–2012 for the whole region (left) and its coastal areas (top and bottom right). The cumulative growth rates were 17% (2000–05), 23% (2000–10), and 47% (2000–12). The right-hand images also illustrate the floodplain's maximum extent (1:1000 annual flood probability) and a non-overlapping flood-safe zone within 300 m from coast.

The choice of a coarser spatial resolution (50 m) than the source data (10/20 m) aims to reproduce urban development processes at a land unit that represents accurately socioeconomic aspects of those processes. The unit of land at which urbanization is simulated must reflect human-behavioral aspects, notably of housing markets and the construction sector. If SLEUTH-3r is calibrated at 10/20 m, state transitions of single grid cells imply that development occurs each time-step at 10 or 20-m patches. These are unrealistically small units of land for actual development in the study area, which is observed at about 50-m patches. Moreover, the objective for higher spatial accuracy, while justified for the coarse data of the past, nowadays entails the danger of moving beyond the scale at which widely accepted processes behind urban growth operate (cf. Fujita, 1983; Anas, Arnott, & Small, 1998; Brueckner, 2011). Accurate digital representation of the city and fidelity of the simulated socioeconomic processes imply obvious trade-offs and the objective is reasonable balance.

The input layers (Fig. 2), sized at 853 × 774 pixels (42.65 × 38.7 km), are derived from governmental open data. The urban layers for seed year 2000 and control years 2005 and 2010 are derived from the Finnish National Land Survey's 10-m SLICES product, a multisource raster representation of land use/cover. Control year 2012 is derived from a 20-m version of EU's CORINE product provided by the Finnish Environment Institute. The rasters were reclassified in GIS software to urban/non-urban and resampled to 50 m using the nearest neighbor method. An empty 50-m vector lattice was then created as the GIS Masterfile that encodes in its attribute table all calibration layers, facilitating quality-checking and consistency. The pixel values of the resampled urban/non-urban rasters were lastly transferred to the lattice by a raster-to-polygon operation.

The transport network is derived for years 2005, 2007, and 2010 from the National Land Survey's 1:10,000 vector topographic database of natural and man-made features. The transport lines were transferred to the GIS Masterfile with a vector-to-vector selection procedure. Ia-b highways and the commuter rail and metro lines are given a pixel value of 100 (high accessibility) and IIa-b roadways a value of 25 (medium accessibility). Initially, the dense network of IIIa-b streets was included with a value of 1 (low accessibility), but was dropped because the chosen spatial resolution misrepresents their influence on urbanization, introducing significant uncertainty in calibration. Commuter rail lines influence directly urban development, since they are included in the transportation layer (vs. informing indirectly attraction-repulsion values). This concurs with historical urbanization in the region that is strongly influenced by commuter rail lines, and is consistent with the region's development strategy that prioritizes the public transport system, including commuter rail.

Slope and hillshade are derived from the Finnish National Land Survey's 10-m digital elevation model (DEM) from 2013. The DEM was resampled to 50 m with a bilinear interpolation algorithm, before calculating hillshade and slope. Slope uses the 'percent rise' algorithm of ESRI ArcGIS, as SLEUTH requires this operationalization of slope.

The exclusion layer is prepared as an exclusion-attraction surface (Jantz et al., 2010), where values of 0–49 denote attraction, 51–100 repulsion, and 50 neutrality toward development. Areas fully excluded from development are assigned the value of 100. These are natural conservation areas according to EU or Finnish legislation, formally designated urban parks, sports and recreation areas, water bodies, and 'no

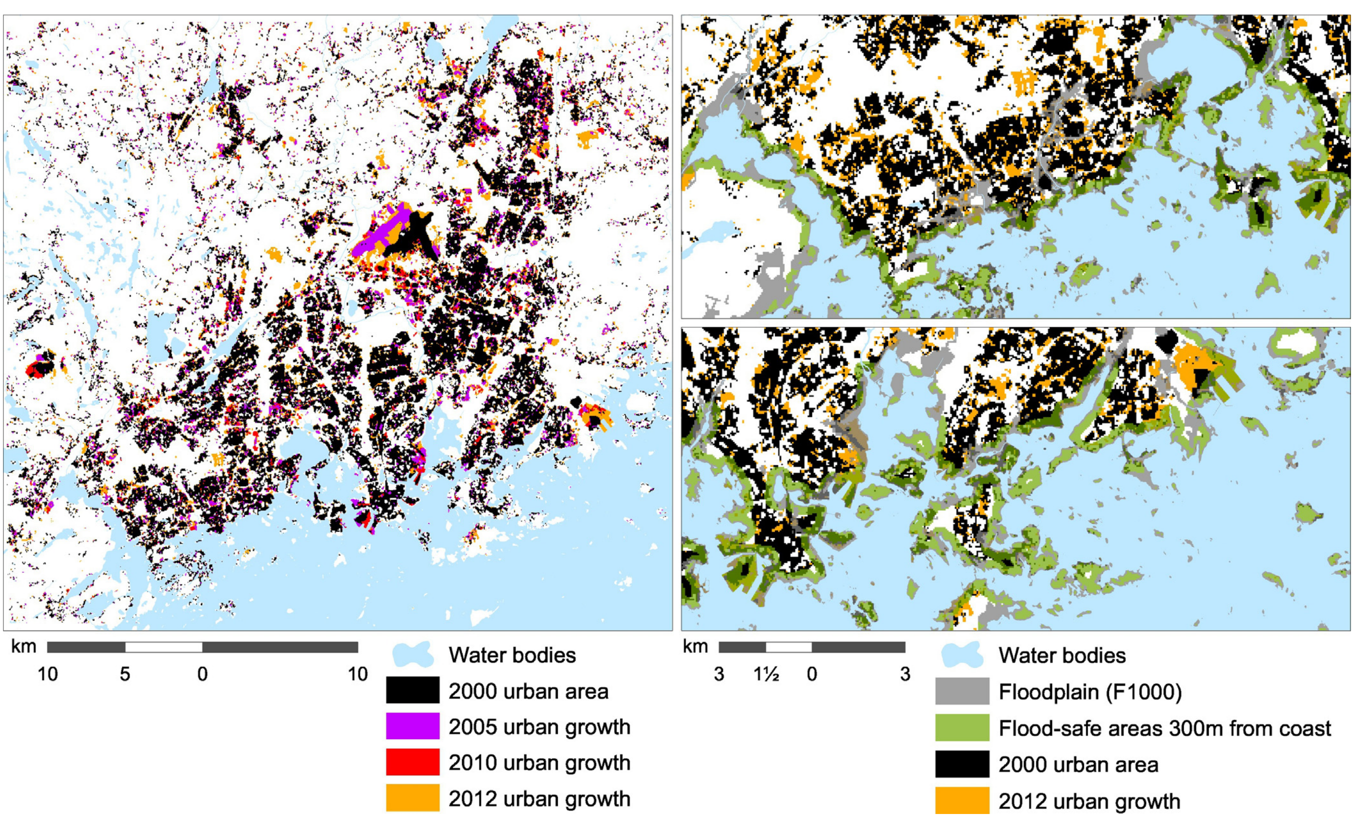

Fig. 1. Observed growth in Helsinki (2000−2012).

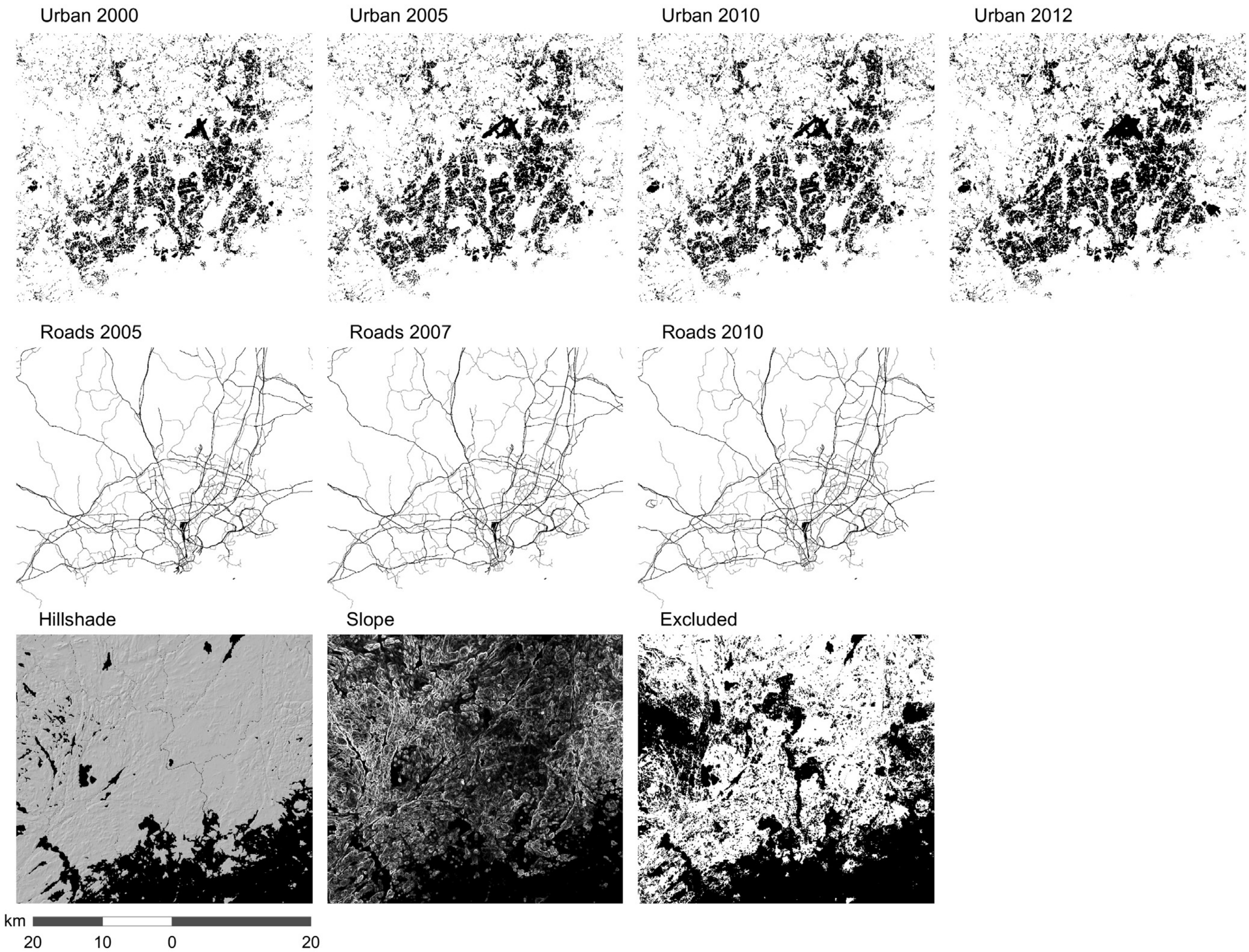

Fig. 2. Inputs; top: urban-nonurban, mid: transport network, bottom: topography and growth constraints.

building rights' areas according to regional plans. These land constraints are derived from NATURA2000 areas provided by the Finnish Environment Institute, protected areas in the aforementioned SLICES product, and zoning maps provided by the Regional Council of Uusimaa. Developable areas are assigned the neutral value of 50. The exclusion-attraction surfaces of the alternative scenarios are described in Section 3.3.

3.3. Scenarios for flood risk management and key assumptions

SLEUTH takes all human determinants of urban evolution as given. They remain latent in the model and urban evolution is modelled via spatial interactions between cells; not human phenomena per se. It therefore assumes that accurately calibrated transition rules emulate how social systems drive urban systems. This determines interpretation of the simulations in connection to not-explicitly-modelled market forces, the planning system, and their relation. Given this feature, three main spatial development scenarios are simulated: 'business as usual', 'market response', and 'development restriction'. Future growth under each scenario is forecast by modifying its corresponding exclusion-attraction layer and using the forecasting growth coefficients identified in calibration (Section 4).

3.3.1. Business as usual (BAU) scenario

This represents the baseline and assumes that the growth patterns of 2000–2012 will continue unaltered until 2040. BAU forecasts future growth by keeping unmodified the exclusion-attraction surface of the calibration stage (Section 3.2). BAU assumes that the city evolves without abrupt changes in the economic and planning system, and the current degree to which the planning system adjusts to or constrains market forces is part of the baseline. If, therefore, this scenario is modified, the differential impacts of the modifications relative to the baseline can be discussed also with respect to differences in the relation of the planning system to market forces.

3.3.2. Market response scenarios (MRa,b)

These assume a bottom-up, information-led adjustment process. MRa translates price/m^2 adjustments in the housing market, following publicly disclosed flood risks, into urban growth adjustments. MRb repeats MRa, but also simulates an active encouragement of development in flood-safe coastal areas. The purpose of this alteration, relative to MRa, is to understand whether reduced growth in flood-prone coastal areas following more transparent flood risks is redistributed automatically to safer areas, or additional measures are needed for reallocation.

Growth adjustments in flood risk zones are based on the sensitivity of price/m^2 adjustments to flood probability identified by Votsis and Perrels (2016) in Helsinki's coastal housing market. They studied non-overlapping treatment (the coastal floodplain) and control (coastal flood-safe areas within 300 m from the floodplain) areas with otherwise similar dwellings and price behaviors, where the differential price effects of flood information on properties indicated as flood-prone versus flood-safe were identified. The discounts in flood-prone properties are sensitive to flood frequency (Table 1); they exhibit bounded-rationality,

Table 1
Calculation of exclusion-attraction values in the market response scenario layers (MRa, MRb).

Flood risk level (Ff; f: return period)	Property price discount[a] (%)	Decline of housing stock[b] (%)	Pixel value in scenario layer
F5	29.49	2.36	89
F10	30.14	2.41	90
F20	25.49	2.04	81
F50	10.39	0.83	51
F100	11.53	0.92	53
F250	13.81	1.10	58
F1000	12.11	0.97	55
In floodplain, protected[c]			50
Within 300 m from coast, flood-safe			50 (MRa); 40 (MRb)
Rest of urban area, no natural protection status			50
Rest of urban area, natural protection status			100

[a] Votsis and Perrels (2016).
[b] Mayer and Somerville (2000).
[c] Ludy and Kondolf (2012).

explained by prospect theory and relating to biases in processing risk information at the tails of the probability distribution (Daniel et al., 2009; Votsis & Perrels, 2016). It is assumed that the price/m^2 discounts in the various flood risk zones can indicate a market-led reduction in the attraction to future development. Mayer and Somerville (2000) support this, showing that relative changes in property prices lead to a change in the growth of the housing stock; their estimates were used to translate the spatially variable drop in housing prices to a drop in the expected housing stock. This relationship was linearly rescaled to the pixel value range of 51–90 to reflect varying degrees of repulsion to development in SLEUTH's exclusion-attraction layer. The increase in price/m^2 and the indications of increased demand for coastal flood-safe areas (Votsis & Perrels, 2016) guide future urbanization in flood-safe areas within 300 m from the coast in two ways. Scenario MRa treats those areas as neutral to development (value of 50) while scenario MRb assigns a 10% attraction premium relative to neutral areas. Flood-safe areas in the rest of the city are neutral to development in order to isolate the impact of coastal interventions. Lastly, developable flood-prone areas indicated by the maps as artificially protected are neutral to development, based on Ludy and Kondolf (2012) who report no flood risk awareness in home owners of protected flood-prone areas. Existing development is assumed unaffected by flood-related restrictions and has a neutral attraction value. Protected natural areas remain excluded from development.

Table 1 summarizes these calculations; note that the various flood-safe and flood-prone areas are non-overlapping. Flood risk levels are denoted by F*f*, where *f* is the return period and 1/*f* flooding probability. For instance, F5 is a flood that occurs at least once in five years (0.2 probability).

3.3.3. Development restriction scenarios (DRa,b,c)

These assume a regulation-led refocus of urbanization that restricts growth in flood-prone areas via top-down zoning, without reference to market behavior. Growth is prohibited in F5-F50 areas (DRa), the entire floodplain (DRb), or F5-F10 areas (DRc), reflecting different planning tolerances to flood risks. DRa assumes that areas with return period $f > 50$ years are neutral to new development, but areas with $f \leq 50$ years are excluded from new development. The 50-year divide is evident in the flood information effect (Votsis & Perrels, 2016) and in flood damage-cost curves (Michelsson, 2008; Perrels et al., 2010). It relates to the maximum time that homeowners expect to own a dwelling: realized house transactions reveal that floods with $f > 50$ years elicit weaker responses than higher frequencies. DRb assumes a more aggressive spatial policy where all flood frequencies are excluded from future development. Conversely, DRc is more relaxed and excludes from new development only areas with $f \leq 10$ years, while other frequencies are neutral to growth. Existing development, inland developable areas, and protected natural areas are treated similarly to BAU and MR.

Note that the BAU scenario represents a future in which urbanization reflects the current relation of the planning system to market forces, and the current attitude of the city and all its determinants toward coastal risks and amenities. In contrast, scenarios MR and DR represent futures in which urban growth responds to the spatial distribution of flood risks. The main difference between MR and DR is in how they constrain growth in the floodplain. Scenarios MR adjust growth by translating information-related price/m^2 adjustments into urban growth adjustments. They therefore translate the spatial redistribution of house prices (due to increased information on the spatial distribution of risks) into a spatial redistribution of growth. Scenarios DR adjust growth in the floodplain without reference to market forces, by imposing arbitrary constraints. Thus, MRa represents a future in which the market responds to the spatial distribution of flood risks and the planning system does not constrain market behavior. MRb represents a future in which, additionally to MRa, planning encourages growth in flood-safe areas. Scenarios DR represent futures in which, regardless of market adjustments, the planning system places its own terms on growth redistribution in the floodplain. While interpretation should be cautious, simulating these differences can indicate how different stances of the planning system toward market forces and the spatial distribution of flood risks affect urban dynamics. Table 2 summarizes all scenarios and pixel values in their exclusion-attraction layer.

Table 2
Scenarios and corresponding pixel values in their exclusion-attraction layer.

	Scenario storylines
Current trend (BAU)	Recent urban growth patterns continue until 2040. Attitudes toward coastal risks and amenities are unchanged, with no specific growth policy in flood-prone areas. The relation of the planning system to market forces remains as before.
Market response (MRa-b)	Urban growth in the floodplain has been redistributed in a bottom-up, information-led manner to better reflect the spatial distribution of flood risks. Redistribution is achieved by referring to flood-risk-related price adjustments in the housing market. The planning system does not constrain market adjustments (MRa) and additionally accommodates demand for flood-safe coastal areas (MRb).
Development restriction (DRa-c)	Urban growth in the floodplain has been redistributed by top-down zoning restrictions without reference to market behavior. The planning system constrains market forces in some areas or deviates from them to various degrees. Growth is prohibited either in F5-F50 areas (DRa), the entire floodplain (DRb), or in F5-F10 areas (DRc), reflecting different planning tolerances to flood risks.

	Pixel value in the exclusion-attraction layer					
	Current trend	Market response		Development restriction		
	BAU	MRa	MRb	DRa	DRb	DRc
Flood-prone areas						
Risk level F5	50	89	89	100	100	100
Risk level F10	50	90	90	100	100	100
Risk level F20	50	81	81	100	100	50
Risk level F50	50	51	51	100	100	50
Risk level F100	50	53	53	50	100	50
Risk level F250	50	58	58	50	100	50
Risk level F1000	50	55	55	50	100	50
Flood-safe areas						
300 m from coast	50	50	40	50	50	50
Rest of urban area	50	50	50	50	50	50
Rest of urban area; building restriction	100	100	100	100	100	100

Table 3
Calibration to observed data with CFD and PFD metrics.

	Calibration stage			
	Coarse	Fine	Final	Forecasting
Growth coefficient				
Diffusion	0–24; 6	1–5; 1	1	1
Breed	0–24; 6	20–28; 2	26	29
Spread	40–60; 5	46–54; 2	50	56
Slope resistance	76–100; 6	90–98; 2	94	42
Road gravity	50–100; 10	52–68; 4	56	61
Fit metric				
|CFD| (|spread|) of top run	0.0223 (0.0308)	0.0218 (0.0318)	0.0209 (0.0241)	n/a
|PFD| (|spread|) of top run	0.0433 (0.0882)	0.0430 (0.0983)	0.0431 (0.0981)	n/a
mean(|CFD|, |PFD|) of top run	0.0327	0.0324	0.032	n/a

Table 4
Performance of the final coefficient set for the control years.

	Edges	Clusters	Population	Mean cluster size	Mean center	Radius	Avg. slope
Observed value							
2000	59,286	5891	97,776	16	447, 391	176	4.54
2005	65,470	6098	114,353	18	447, 384	191	4.48
2010	65,734	5655	119,930	21	447, 384	195	4.43
2012	67,707	5149	143,630	27	450, 376	214	4.41
Simulated value							
2005	64,054 (−1416)	6033 (−65)	114,535 (182)	18 (0)	446, 384 (0, 1)	191 (0)	4.40 (0.08)
2010	67,037 (1303)	5670 (15)	133,000 (13070)	23 (2)	445, 376 (1, 8)	206 (−10)	4.32 (0.11)
2012	67,845 (138)	5454 (305)	140,797 (−2833)	25 (−2)	445, 373 (5, 3)	212 (2)	4.31 (0.10)

Differences from observed in parenthesis (negative values: underestimation; positive values: overestimation).

3.4. Calibration

Calibration identifies the combination of values for SLEUTH's five growth coefficients that best reproduces observed urbanization patterns in the control years. The search is performed with brute force (Clarke et al., 1997) in three successive stages ('coarse', 'fine', 'final') that progressively narrow down the solution space. Fit statistics compare simulated growth to observed growth for all searched coefficient sets. Dietzel and Clarke (2007) developed the optimal SLEUTH metric, while in the context of SLEUTH-3r, Jantz et al. (2010) introduced population fractional difference (PFD) and clusters fractional difference (CFD) as performance indicators of the simulated volume and spatial form of growth, respectively. PFD and CFD range in [−1, 1], where zero indicates perfect fit, positive values overestimation, and negative values underestimation of growth.

Here, calibration was performed with the metrics of Jantz et al. (2010), employing variables |CFD|, |PFD|, their arithmetic mean, and the average spreads of |CFD| and |PFD| between control years. In each calibration stage, a subset was identified that contained Monte Carlo runs within ±5% of perfect fit according to CFD and PFD and with less than ±10% spread in CFD and PFD across control years. Within that subset, the top-performing runs were singled out by sorting by the arithmetic mean of |CFD| and |PFD| and identifying the run where the mean undergoes a sharp rise in relation to the means of the previous (better) runs. This 'first sharp rise' of the mean is assumed to indicate that performance of the subsequent runs decreases rapidly. The search space in each calibration stage was constructed based on Candau (2002: 54–55). Calibration otherwise followed the model's official documentation (http://www.ncgia.ucsb.edu/projects/gig/index.html).

4. Calibration results and validation

The calibrated model's simulated growth does not deviate from observations more than |2.1%| in CFD (ability to simulate urban form) and more than |4.3%| in PFD (ability to simulate total volume of built-up land). The mean of the two indicators is |3.2%|. These values are inside the |5%| range reported by Jantz et al. (2010). The average spread across control years is less than |2.4%| in CFD and less than |9.8%| in PFD. The forecasting growth coefficients are {1, 29, 56, 42, 61}. Table 3 summarizes the calibration stages and CFD and PFD metrics. Table 4 provides additional metrics.

The forecasting growth coefficients translate to growth that occurs mainly as continuous expansion of Helsinki's existing urban clusters, notably along the transport network, by pushing the urban-nonurban edge forward and by filling-in interspersed available land. Spontaneous growth unrelated to existing urban clusters or the transport network is limited. Topographical variation is a moderate influence, in line with knowledge that maximum allowable slope is not heavily regulated in this relatively flat city. The results have commonalities with previous calibrations of Helsinki. Caglioni et al. (2006) report similar road gravity (62) and diffusion (2) coefficients. The setup of Iltanen (2008: 42–43) most closely resembling this study's setup reports similar breed (20) and slope (58) coefficients. Both report significantly lower spread coefficients (10–11). Deeper comparisons are impossible, as their spatial resolution, timeframe, and inputs, differ from the present study.

The images of the forecasting calibration stage were compared to the images of actual growth (Table 5, Fig. 3), indicating a satisfactory performance of the calibrated model in reproducing observed growth (cf. Chaudhuri & Clarke, 2014). These comparisons include the urban pixels of 2000, which can influence upward the estimated accuracy if growth rates are relatively low; this accuracy assessment should therefore be used in conjunction with the metrics of Tables 3 and 4.

Table 5
Accuracy assessment for control years 2005, 2010, and 2012.

Year	Overall accuracy (%)	Kappa coefficient
2005	95.92	0.86
2010	93.77	0.80
2012	92.19	0.77

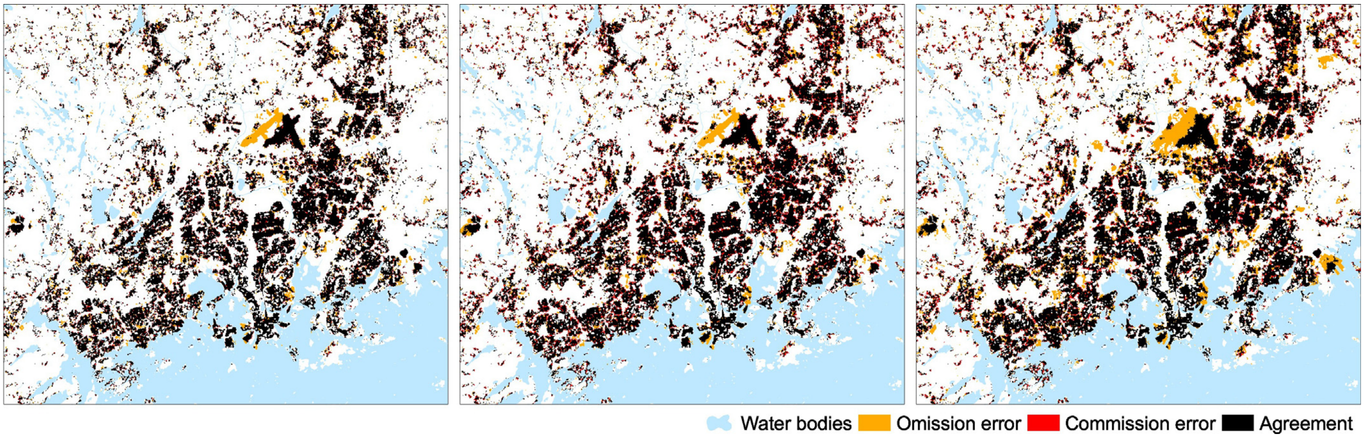

Fig. 3. Simulated versus observed growth in control years 2005 (left), 2010 (center), and 2012 (right).

5. Scenario forecasts

Each scenario's trajectory is discussed by firstly focusing on aggregate characteristics for the whole urban region, followed by spatially disaggregate characteristics in the coastal and near-coastal areas.

5.1. BAU scenario

Fig. 4 summarizes the business-as-usual scenario. The simulation uses the last available data (Fig. 2, Section 3.2) and illustrates the future trajectory of current urbanization trends with no change in land constraints, transport network, and no serious exogenous shocks in population and economic structure. BAU assumes that development behavior inside the floodplain continues without interventions specific to flood risks. The market response and development restriction scenarios simulate changes in development patterns in the presence of flood-related interventions.

Fig. 5 summarizes growth indicators under BAU. The growth rate of built-up land is 2.7% until 2020, steadily dropping to 1.3% by 2040. This corresponds to almost a doubling of built-up land ('pop'), from 39,000 to 66,000 ha. The net length of the urban/non-urban frontier ('edges') does not change significantly, increasing weakly until 2030 and declining subtly afterwards. The growth of total built-up land while maintaining the length of urban/non-urban edges implies that, additionally to an overall decrease of natural land, progressively fewer neighborhoods maintain direct access to natural patches. More precisely, the number of built-up clusters ('clusters') decreases steadily while their size ('cluster size') increases, indicating that Helsinki's built-up morphology consolidates and becomes less fragmented. This links to Helsinki's past development practices that have used ample space, preferring sprawling low-density residential areas, without a comprehensive preservation plan for green infrastructure. As developable land diminishes, the saturation of built-up areas implies that the loss of large natural areas found mainly at the urban periphery is coupled with the loss of

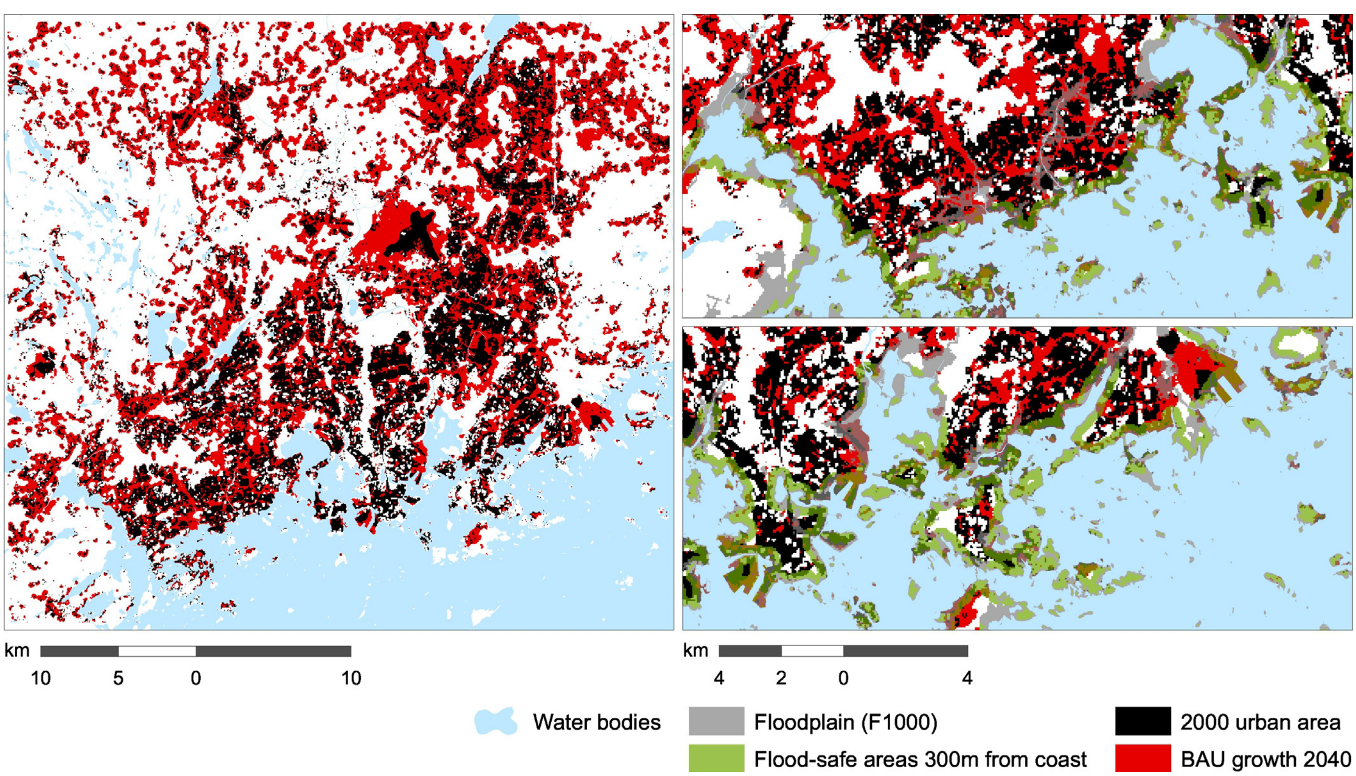

Fig. 4. Urbanization under scenario BAU by 2040.

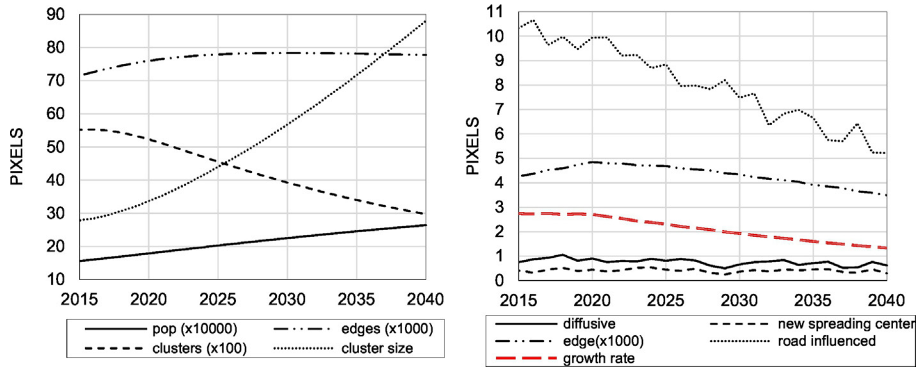

Fig. 5. Volume and form (left) and growth types (right) under BAU. One pixel corresponds to an area of 50 m^2 (0.25 ha).

small green spaces located between built-up clusters across the entire city.

Edge growth is orders of magnitude larger than the other growth types, indicating that Helsinki spreads from existing built-up areas, with limited leap-frogging, and fills-in natural areas between neighborhoods. Emerging areas from spontaneous and new spreading center growth are minimal. Road-influenced growth is active throughout the forecast timeframe, but declines steadily, because no new major transport links are simulated and therefore any road-influenced growth is gradually saturated around existing high-access links.

In Helsinki's residential areas, most unbuilt land is green infrastructure. Its loss represents increased disaster risk, as the lost ecosystem services regulate flooding (Davies et al., 2011; De Groot et al., 2002) and loss of property value from decreased proximity to green areas (Brander & Koetse, 2011). Concurrently, the consolidation of impermeable areas exacerbates flooding and impacts, including damages of storm-related flooding. Therefore, Helsinki's BAU scenario represents an increase in physical vulnerability (loss of regulating ecosystems), economic vulnerability (loss of value in the housing market), and exposure to flood-related hazards (increase and consolidation of urban areas).

A closer examination on BAU's local characteristics is important. In addition to the seven coastal flood risk zones (F5-F1000), and as the morphology of these zones is fragmented, indicative flood-safe areas were explored at 0.3, 0.3–1, and 1–10 km from the coastline. The distance of 0.3 km is grounded in the homogeneity of high-value properties inside this buffer, in terms of market behavior and physical characteristics. Between 0.3 and 1 km from the coast, one observes a second zone of coastal properties that are of high value, but do not belong to the far-right end of the price range. Properties between 1 and 10 km from the coast are assumed as representatives of the inland housing market.

These local characteristics were measured by applying a 90% threshold to the scenario's cumulative urbanization probability map of year 2040 (Table 6). Since the predicted urban pixels are expressed in probability of cumulative urbanization by a given year, it is assumed that 10% is a reasonable uncertainty for the model's predictions. The total amounts of predicted built-up cells where counted for the flood risk and flood-safe zones.

Table 6
Local characteristics of the BAU scenario for year 2040 (10% uncertainty).

Zone	Built-up land in 2040		% change from 2012
	Pixels	Hectares	
F5	4636	1159	66.0
F10	422	106	47.6
F20	429	107	44.0
F50	584	146	46.0
F100	1640	410	69.6
F250	635	159	30.4
F1000	1175	294	41.4
Flood-safe (0.3 km from coast)	8226	2057	18.6
Flood-safe (0.3–1 km from coast)	96,415	24,104	39.9
Flood-safe (1–10 km from coast)	16,211	4053	24.0

Note that counting the growth in these zones as separate from each other represents an assumption behind flood risk mapping and economic analysis. For instance, although F1000 and F5 zones partly overlap, separate inundation maps are produced per return period, which can communicate conflicting information. Economic analysis also assumes that the housing market's response is a compound result of multiple maps. Future research needs to clarify these assumptions and further explore how markets react to areas that are flood-safe in some return periods but unsafe in others. Another question is the relation between binary classifications sound for engineering analysis versus overlapping classifications used by the public and markets. Considering the above, this study adopted the compound effect assumption for the BAU scenario for rendering its trends comparable to those of the DR and MR scenarios, which contain compound market effects.

The floodplain is set for notably higher growth (30–70% relative to 2012) than waterfront flood-safe areas (19% within 0.3 km from coast) and inland areas (24% 1–10 km from coast). The transition between coastal and inland areas (between 0.3 and 1 km from coast) is the exception, with 40% of growth relative to 2012. The floodplain's high growth rates correspond to prior research (Bin et al., 2008; Daniel et al., 2009) that finds that coastal amenities overdrive decisions in housing markets. Here, the BAU simulation confirms that urbanization drivers over-respond to amenities and under-react to flood risks. Intense growth in risky areas challenges Helsinki's resilience to current flood risks and its adaptation strategy to future costal risks. A significant portion of the regional economy's resources is channeled toward growth in risky coastal areas instead of safer areas or being invested, e.g., into additional insurance and protection. It represents an increase in society's exposure and vulnerability to flood risks, as large volumes of urban development imply large volumes of residential building stock, public infrastructure, and population.

5.2. Market response scenarios

Fig. 6 displays the simulated output of scenarios MRa and MRb near the coast. These scenarios translate the housing market effects of flood risk information into urban development effects, for better assessing its nature as an adaptation policy instrument. They assume that the planning system adjusts to market forces rather than constraining them. The difference between MRa and MRb is that the former assumes no planning intervention in flood-safe areas within 300 m from the coast, whereas the latter assumes a 10% attraction premium in those areas relative to all other flood-safe areas.

The information effect translates into fewer built-up areas, 0.8% (MRa) and 0.7% (MRb) relative to BAU (Fig. 7 left). Growth rates are

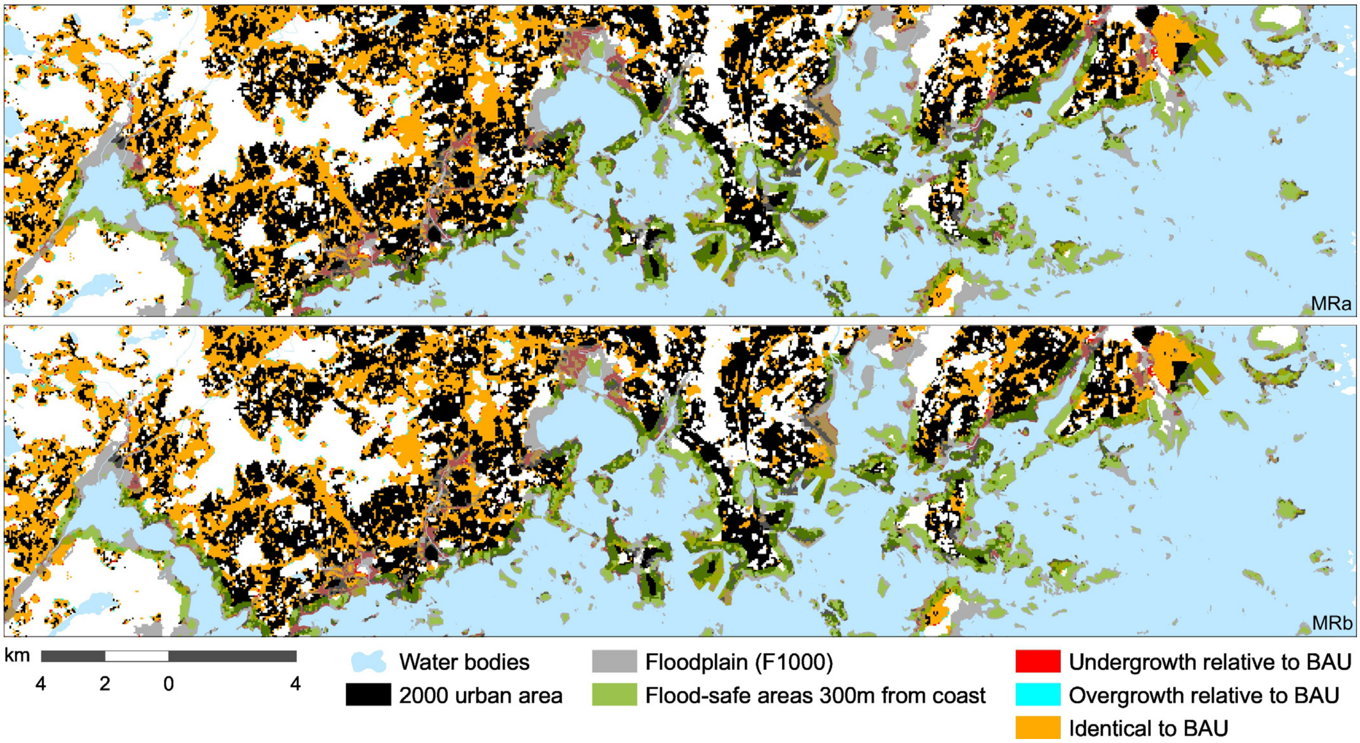

Fig. 6. Urbanization under scenarios MRa (top) and MRb (bottom) by 2040.

initially subdued by about 0.06% in both scenarios, but recover to BAU levels in 2033 (MRb) and 2034 (MRa) (Fig. 7 center). Subdued growth in risky areas can be beneficial, but discussing the implications is limited by using only SLEUTH. Deviations from BAU growth are small and the indirect economic effects of slightly reduced building production are likely moderate, if the fluctuations of the deviations are moderate and the instability does not last long. However, Helsinki has a deficit in the provision of residential and work floorspace. If reduced growth rates are applied to a city with unmet demand for floorspace, m^2-prices may react strongly during the forecast's initial period. Such a price increase can have more significant consequences.

Morphologically, MRa yields 2% more urban clusters that are 3% smaller in size relative to BAU, whereas MRb yields 1.6% more, 2% smaller clusters (Fig. 8). This indicates that the simulated policy instrument fragments baseline urban morphology (see Section 6 for implications). Additionally, the MR scenarios impact the amount of urban-nonurban edges and of edge growth, which is BAU's main growth component. The production of edges undergoes a negative shock relative to BAU until about 2028, re-bouncing with higher amounts until 2040 (Fig. 7 right).

Fig. 9 displays the scenarios' local deviations from BAU. In the floodplain, most deviations appear to follow pre-set differences in the exclusion-attraction layer, indicating that model output is responsive to modifications in development constraints. However, there are subtle indications of non-trivial spatial spillovers of the constraints. Although MRa-b impose identical restrictions (exclusion-attraction values) in all flood risk zones, they impact urbanization inside these zones differently, presumably because they impose different assumptions in the contingent flood-safe zone of 300 m within coast; MRb assumes a planning system that accommodates the increased demand for coastal but flood-safe properties. This spillover may reflect SLEUTH's ability to capture how growth in one area is impacted by restrictions in contingent areas, but requires a closer look on how a neighborhood of cells interacts during growth cycles before making policy-relevant assertions. Moreover, scenario MRb, which only slightly elevated the attraction of coastal flood-safe areas relative to MRb, is the only scenario with a positive deviation of 1.7% in produced built-up land relative to BAU in these flood-safe areas, whereas relative growth under MRb is surprisingly negative at −0.5%. MRa and MRb affect growth in inland flood-safe areas (0.3–10 km from coast) in a similar manner.

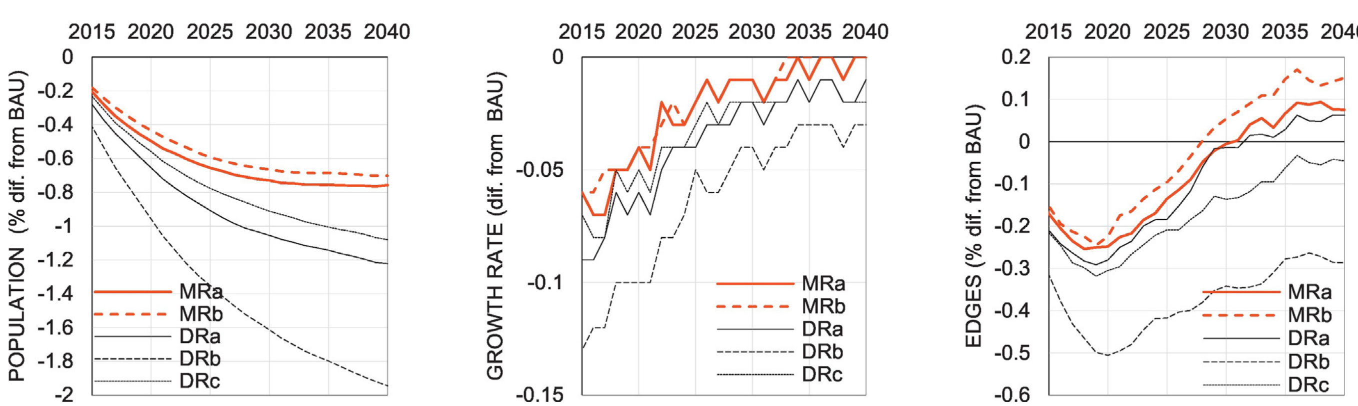

Fig. 7. Deviations from BAU in the amount (left) and growth rate (center) of built-up land production, and in the amount of produced urban-nonurban edges (right).

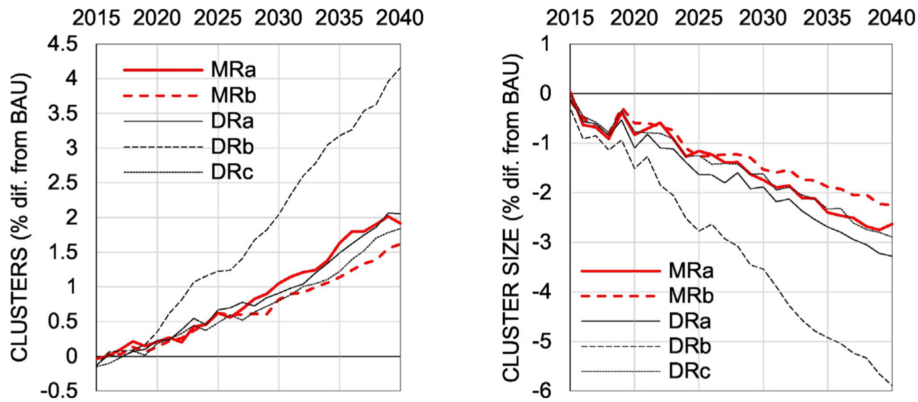

Fig. 8. Deviations from BAU in the amount (left) and average size of urban clusters (right).

Given SLEUTH's assumptions (Section 3.3), if the aforementioned spillover is not a misleading feature of spatial interaction in the model (cf. Gibbons & Overman, 2012), the following can be suggested. If increased demand for coastal flood-safe areas is accommodated by the planning system (MRb, i.e. reflecting demand via the exclusion-attraction surface; Table 2), this yields a redistribution of urban development in the floodplain that is different from when planning does not encourage demand for coastal flood-safe properties (MRa). Moreover, growth differences between MRa-b indicate that if planning does not actively respond to demand changes due to flood risk disclosure, redistribution of development toward coastal flood-safe areas does not materialize.

5.3. Development restriction scenarios

Further insights are gained by the DR scenarios, which apply regulatory restrictions of new growth in the floodplain without reference to the nuances of the housing market's response to different flood probabilities. It is thus assumed that the planning system constrains, rather than adjusts to, market behavior. Figs. 7–9 overview growth indicators under DRa-c. Fig. 10 visualizes growth in the coast under the most deviant scenario, DRb. DRb is interesting also in the sense that, although flat-out zoning restrictions in the entire floodplain are unlikely, they can be a de facto situation if sea level rise renders the floodplain undevelopable. This topic is beyond this study and obviously contains an untested assumption that sea level rise happens at once and coincides with the floodplain.

Urbanization volume (Fig. 7 left) and growth rate (Fig. 7 center) are impacted the most by the aggressive scenario (DRb), whereas the relaxed (DRc) and middle-way (DRa) scenarios keep near the market response scenarios. DRb yields 1% (2020) and 2% (2040) less built-up land relative to BAU, whereas the impact of DRa and DRc is 0.6 (2020) and 1.1% (2040). DRb subdues growth rate by 0.1% (2020) and 0.03% (2040) relative to BAU, whereas DRa and DRc stay close to MRa-b. Note that no DR scenario recovers to BAU's growth rate, whereas the MR scenarios recover by 2034.

DR produce more fragmented urban morphologies relative to BAU (Fig. 8). DRb stands out with 4% higher amount of built-up clusters that have 6% smaller size relative to BAU by 2040. The morphological impacts of DRa and DRc are entangled with those of the MR scenarios; DRa produces 2.1% more urban clusters that are 2.9% smaller relative to BAU, while the respective quantities under DRc are 1.8% and 3.2%. Concerning the amount of urban-nonurban edges (Fig. 7 right), DRa trails just below MRa-b; it takes an initial hit by producing in 2020–0.3% edges relative to BAU and re-bounces after 2030 with +0.1% more edges.

Regarding local effects (Fig. 9), it is noteworthy that DRb's exclusion policy for the entire floodplain yields a −1.6% deviation from BAU in produced built-up land in the 0–0.3 km coastal flood-safe zone, while DRa and DRc have deviations of −0.5%. The exclusion-attraction values

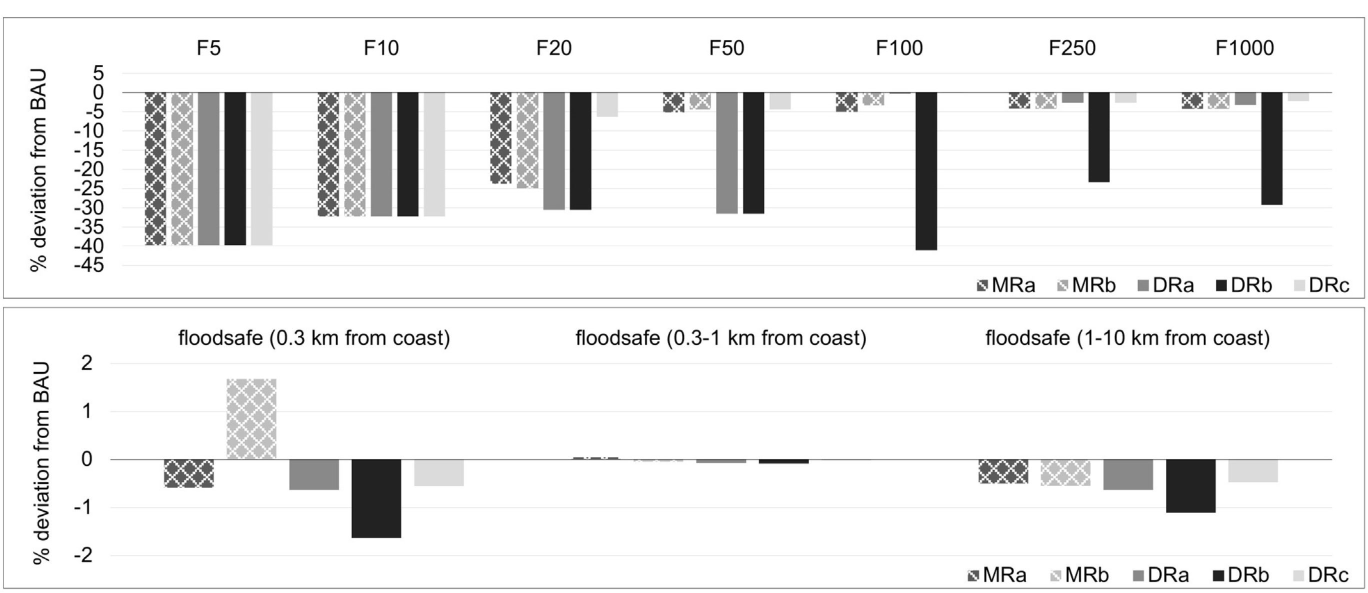

Fig. 9. Deviations from BAU in built-up land in 2040 in flood-prone (top) and flood-safe areas (bottom).

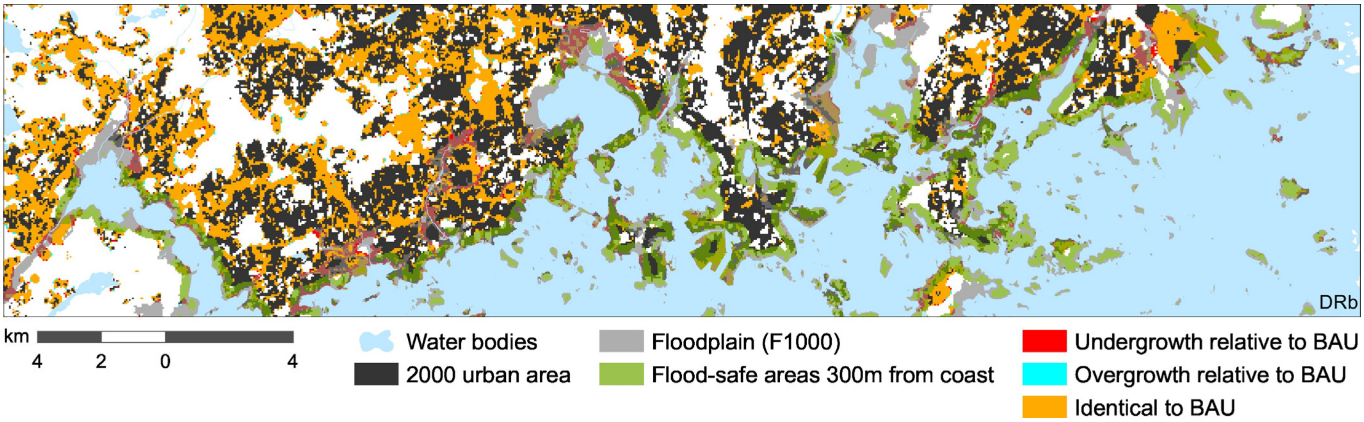

Fig. 10. Urbanization under scenario DRb by 2040.

in this area are identical (neutral) in all scenarios, except MRb (attraction of growth). This links to earlier conclusions: demand for flood-safe locations will not automatically translate to refocusing of development; the additional implication here is that regulation that is entirely insensitive to different flood probabilities impacts flood-safe areas stronger than spatially flexible approaches.

Lastly, all scenarios have near-zero deviation from BAU in flood-safe areas between 0.3 and 1 km from the coast whereas differences reappear in the 1–10 km flood-safe areas; these two zones have identical constraints in all scenarios. This may connect to spatial spillovers of constraints, but a closer look is needed on how growth potential in the entire modelled area is affected by localized restrictions.

6. Conclusions

The simulations show that growth constraints inside the floodplain fragment urban growth (smaller and more clusters) relative to the baseline, implying a larger proportion of built-up land proximate to ecosystem services. Planning interventions restricting growth in the floodplain can thus decelerate urban consolidation, which, combined with decelerated growth, may encourage the preservation and interspersion of ecosystem services, including flood-regulation. Alleviating the loss of interspersed ground-based ecosystem services can preserve wealth in housing markets, thus reducing vulnerability, while increasing the exposure of residential areas to ecosystem services. However, the impacts of reduced growth across urban economic sectors must also be accounted for. Different land constraints yield a differential redistribution of urbanization in and near the application area, whereas demand for amenity-rich safe locations does not translate to a redistribution of growth in those areas, unless actively encouraged. An intervention's spatial character is therefore important, as interventions that track and respond to market adjustments caused by increasingly transparent climate-related risks appear necessary for refocusing urban development. The planning system's tolerance to flood risk and market behavior is therefore a potentially important parameter in the way wealth and investment (capital stock and infrastructure) are distributed in relation to climate-sensitive risks and amenities. Note, however, that urban development interventions, unless very strongly growth-depressing, usually entail development in zones not originally considered, which may in turn face not-yet-considered hazards; care should be exercised to avoid shifting problems rather than solving them.

It is unclear whether planning interventions *fully* following market responses are preferable over ones that pose ad hoc but gentle restrictions informed by flood risks. Excluding the entire floodplain from future growth translates to reductions of 25–40% in produced built-up land relative to the baseline. This illustrates the volume of development anticipated in the floodplain without intervention, but also shows that regulation with zero reference to market forces subdues a tremendous amount of growth. All other, less restrictive, scenarios achieve results similar to each-other, regardless of how they quantify growth restrictions. This strengthens the view that development restrictions that are spatially flexible in the floodplain, rather than monolithic, redistribute growth more elegantly without inducing shocks that intuitively appear problematic. Moderate, rather than very restrictive, zoning measures, adjusting to rather than constraining market behavior, may work better for hazard management, provided the considered hazards are not lethal.

An open question remains about how unrealized growth potential is handled in SLEUTH and whether alternative models redistribute growth differently. This requires an exploration of how cellular automata calculate growth potential *independently* of how they spatially distribute realized growth, and references to microeconomic theory that explains how regional and national economic output is distributed over an urban area through investment and the location decisions of firms and households. In this respect, incorporating econometric estimations into SLEUTH is useful, but the defining parameter is how the estimates are translated to pixel values; there can be alternative approaches.

Lastly, SLEUTH's distinguishing feature in navigating alternative urban futures is distributing urban growth at a fine geographical grid, which is important in vulnerability and exposure assessments. This feature will be boosted if coupled to models that can assess the costs and benefits of SLEUTH's scenario forecasts (urban microeconomic models; land use transport integrated models; regional CGE models), but cannot distribute growth at a fine resolution grid as SLEUTH does.

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