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# Assessing the dynamics of urban vulnerability to climate change: Case of Helsinki, Finland

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ABSTRACT

Future climate risk is not only dependent on future climatic changes but also on how exposure and vulnerability develop in the future. There is a gap in understanding what drives future climate vulnerability, and how to account for its spatial emergence. This issue is particularly pertinent for cities due to the concentration of assets and population at risk, and rapid socio-economic and land use changes. We develop a mixed methods approach, which integrates quantitative, qualitative and participatory methods to (1) identify internal and external drivers of socio-economic development and land use change, (2) explore a range of future pathways using local socio-economic scenarios, and (3) visualize changes in vulnerability indicators with the help of a participatory mapping exercise. We test the approach in the City of Helsinki with the timeframe up to 2050. Our results show the connections between the drivers and changes in vulnerability indicators, while maps developed in a stakeholder workshop visualize the potential spatial changes in indicators. Our approach of connecting indicators, drivers and adaptation/planning needs, as well as scenario analysis, provides a deeper understanding of vulnerability dynamics as a process and provides insights for different sectors of urban policy and planning.

## 1. Introduction

Assessing future climate risks includes accounting for both climatic (hazards) and non-climatic (exposure and vulnerability) factors (Oppenheimer et al., 2014). While the overall number of future-oriented risk assessments is growing, most of them only account for the future climate, neglecting the change over time (i.e. dynamics) in exposure and in particular vulnerability (Jurgilevich et al., 2017; Ford et al., 2018; Bennett et al., 2016; Mcdowell et al., 2016).

On the one hand, vulnerability dynamics can be captured as a projected state, similar to assessing current vulnerability. The most common way to assess future vulnerability at the sub-national level is usually done with similar methods: mapping aggregated vulnerability indices using statistical projections and trend extrapolations to identify hot-spots of vulnerability, i.e. areas where vulnerability will be high and need to be prioritized in adaptation planning (Jurgilevich et al., 2017).

On the other hand, vulnerability dynamics can also be treated as a process. This approach has been non-existent in future-oriented studies, and theoretical and methodological development is needed. Assessing vulnerability dynamics as a process means looking at what drives changes in vulnerability and reconstructing vulnerability development pathways (Jurgilevich et al., 2017; Räsänen et al., 2016; Dilling et al., 2015; Bennett et al., 2016; McDowell et al., 2016). The Intergovernmental Panel on Climate Change (IPCC, 2014b) states with high confidence that various factors (e.g. wealth distribution across society, demographic factors, migration, employment, and governance) influence vulnerability and that the drivers interact (Oppenheimer et al., 2014; Räsänen et al., 2016; Otto et al., 2018; Bennett et al., 2016). Current understanding of drivers, their interlinkages, as well as indirect and cascading effects of socio-economic changes on future vulnerability is limited and needs to be studied further (Ford et al., 2018). This presupposes acknowledging system complexity in the assessments, embedding vulnerability in a socio-economic context, and accounting for cross-scale interactions (Ford et al., 2018; Dilling et al., 2015; O'Brien et al., 2007).

The limited consideration of vulnerability dynamics has implications for policy and planning, since adapting to future climate risks usually starts with a climate risk and/or vulnerability assessment (Adger et al., 2018; Preston et al., 2011; de Sherbinin et al., 2019). Previous studies have brought forward the unsatisfactory uptake of risk assessments results in policy-making and planning, suggesting that this may be due to the low usability of (non-)climate information, neglect of institutional

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context, and underlining functionalism in climate and non-climate services (Ford et al. 2018; Dilling and Lemos, 2011; Biesbroek et al., 2015; Wellstead et al., 2017). Accounting for vulnerability dynamics as a process can be useful for anticipatory and preventative action in policy and planning (Adger et al., 2018).

Understanding and assessing vulnerability dynamics is most pressing in the urban context. Cities are centers of population growth and economic activity (Hallegatte and Corfee-Morlot, 2011; Viguié et al., 2014), which means that there is a concentration of population and valuable assets that can be impacted by climate change. Furthermore, the socio-economic change happens at a more rapid pace in cities; thus, assessing current vulnerability has little value for medium and long-term policy and planning (Romero-Lankao et al., 2012; Birkmann et al., 2015). The urban form and socio-economic activities can potentially amplify cities' vulnerability to climate change impacts (Apreda et al., 2019; Revi et al., 2014), meaning that to assess cities' vulnerability and climate risk, special attention should be paid to cities' socio-economic development and urban form.

The objective of the study is driven by the methodological and conceptual gaps discussed above: to advance the understanding of urban vulnerability dynamics and to advance the methodological base to account for it. We develop and apply a mixed methods approach to explore the dynamics of climate change vulnerability of urban population as a process and to visualize the changes spatially. We identify the key drivers of change, use a range of urban socio-economic and land use change scenarios, and utilize a participatory SoftGIS tool (Rantanen and Kahila, 2009) to map changes in vulnerability indicators. We test the approach in the City of Helsinki and analyze changes in vulnerability up to 2050, based on three scenarios. Our approach provides an understanding of possible future socio-economic and land use developments by identifying key drivers of change and exploring a range of socio-economic scenarios. The maps developed in a stakeholder workshop document the changes in vulnerability indicators spatially. Finally, the integrated analysis of scenarios in conjunction with the maps demonstrates how the key socio-economic drivers influence vulnerability and explores spatial patterns in indicator changes. The overall understanding and demonstration of the complex processes that influence future vulnerability contribute to the conceptual and methodological development of the field.

## 2. Key concepts and methodology

### 2.1. Key concepts

We follow the IPCC climate risk framework, concepts and definitions with climate risk as a function of hazard, vulnerability, and exposure (Oppenheimer et al., 2014). Vulnerability is defined as "the propensity or predisposition to be adversely affected" and refers to the socio-economic characteristics of an object at risk (IPCC, 2014a, p. 1775). Drivers of vulnerability are "agents or processes outside the climate system that influence a human or natural system" (IPCC, 2014a, p. 1769), which means that vulnerability drivers are non-climatic factors related to socio-economic development (IPCC, 2014b). We consider vulnerability as a pre-existing condition, i.e. vulnerability is due to certain socio-economic characteristics of an object at risk that make it susceptible to potential impacts (Joakim et al., 2015), and we build on the previous study of current vulnerability in Helsinki conducted by Kazmierczak (2015). Thus, we operationalize vulnerability as a function of several aspects: sensitivity (*personal* factors pertaining to the personal characteristics that increase the likelihood of being adversely affected, for example, age, education or health status), adaptive capacity (*social* factors pertaining to social environment and financial situation, influencing the ability to prepare, respond, and recover, for example, social inequality and income), and enhanced exposure (*environmental* factors pertaining to physical environment that exacerbate or alleviate the severity of hazard impacts, for example, housing, green areas, permeable surfaces, state of infrastructure) (Fig. 1) (Kazmierczak, 2015). Since vulnerability is a theoretical concept and not a directly measurable phenomenon (Hinkel, 2011), it is often assessed through indicators. Indicators are functions from observable variables (Gallopin, 1997) used to map one observable variable to one theoretical variable (Hinkel, 2011). In this study, we adopt the indicators and proxies as they were developed and justified in Kazmierczak (2015).

### 2.2. Methodology

We use mixed methods approach (Johnson et al., 2007; Ghiara, 2020), integrating quantitative, qualitative and participatory methods for data collection and analysis. The study relies on the sequential mixed methods design, i.e. results of one method inform the other (Morse, 1991). The rationale to use mixed methods design is study development, probing new datasets, enriching the data and augmenting the results interpretation (Greene et al., 1989; Collins et al., 2006). We used qualitative methods in scenario and map analysis to establish links between driver changes and reflect indicator changes visually, and quantitative methods to evaluate spatial patterns in the maps. The research question of the study presupposes the lowest degree of participation, i.e. "contractual" participation limited to the data collection from the experts (Probst and Hagmann, 2003; Barreteau et al., 2010; Hurlbert and Gupta, 2015), while the study is designed and framed by the researchers. Participatory methods are especially useful in future-oriented assessments and in dealing with complex phenomena, where future cannot be predicted with traditional scientific techniques (Salter et al., 2010). Moreover, they allow tailoring the methodology to the local context and overcoming data availability challenges.

Our methodological approach is divided into three stages responding

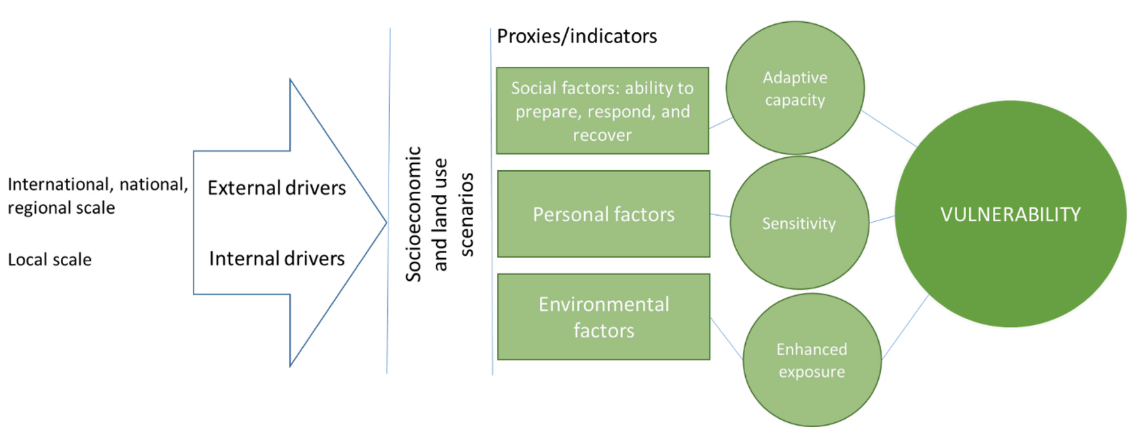


**Fig. 1.** Operational framework. Based on (Kazmierczak, 2015; Bennett et al., 2016; Oppenheimer et al., 2014).

**Table 1**
Methods and data sources in each step of the methodology.

| Stage | Step | Type | Data sources |
|---|---|---|---|
| 1: Drivers | 1: Literature review of drivers of socio-economic and land use change | Conducted solely by the authors | Sampled literature listed in Jurgilevich et al., 2017; socio-economic scenarios developed by the Helsinki administration for the Helsinki Master Plan 2050 |
| | 2: Expert validation and elicitation of the drivers | Empirical data collection | A face-to-face meeting with two practitioners from the City administration, an online survey to climate change and urban planning researchers from Aalto University and University of Helsinki |
| 2: Scenarios | 3: Ranking questionnaire on the validated socio-economic and land use change drivers | Empirical data collection | An online ranking questionnaire targeted at the practitioners from the City administration |
| | 4: Integration of the key drivers into the socio-economic scenarios | Conducted solely by the authors | Socio-economic scenarios developed by the City administration for the Helsinki Master Plan 2050 |
| 3: Mapping | 5: Construction of a SoftGIS survey of vulnerability indicator changes using the socio-economic scenarios | Conducted solely by the authors | The indicators for the SoftGIS survey are drawn from the previous study of current social vulnerability in Helsinki (Kazmierczak, 2015) |
| | 6: Participatory mapping of vulnerability indicator changes with the SoftGIS survey in a stakeholder workshop | Empirical data collection | Participatory mapping in a stakeholder workshop, participants from the City administration |

to the identified research gaps: the need to understand drivers (Stage 1) and their interlinkages (Stages 2 and 3), indirect and cascading effects of socio-economic changes on future vulnerability while acknowledging system complexity in the assessments (Stage 3), embedding vulnerability in a socio-economic context (Stage 3), and accounting for cross-scale interactions (Stages 2 and 3) (Ford et al., 2018; Dilling et al., 2015; O'Brien et al., 2007). The stages are further detailed with six steps (Table 1), the specific case application is elaborated step-by-step in Supplementary materials 1.

The experts engaged in the study included researchers (Step 2) and city administration practitioners belonging to the climate change and adaptation working group of the City of Helsinki (all participatory steps of the study, i.e. Steps 2, 3, and 6). The working group consisted of 24 members from city planning, environment, construction, safety and preparedness, rescue services, and social and health services. In step 2, two practitioners and seven researchers focusing on climate change and urban planning participated in expert validation and elicitation (Table 1). In step 3, ten practitioners responded to the ranking survey (Table 1). In step 6, eleven practitioners took part in the participatory mapping workshop (Table 1). Two of the practitioners participated in all three participatory steps (2, 3 and 6), and many of the participants were the same in steps 3 and 6.

In **Stage 1**, we identified the drivers of future socio-economic development and land use change (Bennett et al., 2016; IPCC, 2014b) with a literature review and validated them with expert elicitation (Table 1). Expert elicitation was done with the help of two practitioners

**Table 2**
Chosen indicators in the SoftGIS questionnaire, their justification based on Kazmierczak (2015), and the question in the SoftGIS questionnaire.

| Vulnerability dimension | Aspect of vulnerability | Indicator | Justification and link to planning/adaptation needs | Question for SoftGIS questionnaire |
|---|---|---|---|---|
| Enhanced exposure | Physical environment | Green areas | Green areas have a cooling effect in case of heat waves as well as serve as a natural drainage outlet in case of increased precipitation | 1. Can you mark the locations where the green areas may reduce significantly? |
| | | New residential areas | New residential areas are used to indicate newly developed districts where an influx of new citizens may occur. That should be considered in adaptation planning, particularly if new area development occurs at a loss of green space | 2. Can you mark the areas where new residential areas will be built? |
| | Infrastructure and housing | State of residential buildings | Residential areas that are in need of retrofitting, depending on the building type, may not provide enough cooling effect in heat waves or may not have enough capacity to withstand severe flood events | 3. Can you mark the areas where residential buildings are getting old and need retrofitting? |
| | | State of critical infrastructure | Critical infrastructure (water supply, storm water drainage, electricity, road network) may not have enough capacity to withstand climate hazards or critical weather events | 4. Can you mark the areas where critical infrastructure (energy, water, etc.) is getting old and needs modernization? |
| Adaptive capacity | Occupancy | Population density | Areas with high population density are associated with more challenges in times of evacuation and providing accommodation in recovery phase | 5. Can you mark the areas where population density will be high?<br>6. Can you mark the areas where population density will be low? |
| | Economic and social inequality | Housing prices | Housing prices may serve as a proxy for income. Citizens with higher income have a higher ability to prepare for floods and heatwaves by investing in structural modifications to houses as well as are more likely to insure property from loss & damage | 7. Can you mark the areas where the housing prices may increase significantly?<br>8. Can you mark the areas where the housing prices may decrease significantly? |
| | | Social inequality (district segregation) | Social inequality by district serves as a proxy for income (similarly to housing prices) and indicating capacity to prepare, respond, and recover in cases of floods or heatwaves | 9. Can you mark the areas where social inequality may increase significantly? |

**Table 3**
List of drivers after the ranking. Key drivers are marked with bold font.

| List of drivers | Average score | Standard deviation | Min-Max | Driver level (Internal / External) |
|---|---|---|---|---|
| Demographics | | | | |
| 1. Migration (in and out) | 4.4 | 0.66 | 3−5 | Internal/External |
| 2. Demographic structure change: increase of elderly people (+65 years old) | 3.8 | 0.60 | 3−5 | Internal |
| 3. Population growth in Helsinki | 3.2 | 0.87 | 2−5 | Internal |
| 4. Demographic structure change: influx of young people (20−30 years old) | 3.2 | 0.87 | 2−5 | External |
| 5. Demographic structure change: increase of small children (0−7 years old) | 3.1 | 0.70 | 2−5 | Internal |
| Economy | | | | |
| 6. State of economy at the national level | 3.9 | 0.70 | 3−5 | External |
| 7. Change in the source of energy (national level) | 3.8 | 0.98 | 2−5 | External |
| 8. Energy production (centralized/decentralized at the national level) | 3.8 | 0.87 | 2−5 | External |
| 9. Values and consumption patterns of citizens (e.g., sharing economy, sustainable consumption) | 3.7 | 0.64 | 3−5 | Internal/External |
| 10. Growth of work places in Helsinki | 3.7 | 0.78 | 3−5 | Internal |
| 11. Trade | 3.6 | 0.92 | 2−5 | External |
| 12. Availability and use of natural resources (land) | 3.4 | 0.80 | 2−5 | Internal |
| 13. Public sector as the main actor | 3.4 | 0.80 | 2−5 | External |
| Governance | | | | |
| 14. Mitigation policies | 4 | 0.63 | 3−5 | External |
| 15. Environmental policies | 4 | 0.63 | 3−5 | External |
| 16. National regulation and legislation | 3.9 | 0.54 | 3−5 | External |
| 17. Municipality structure (related to decision-making) | 3.8 | 0.75 | 3−5 | External |
| 18. Political leadership in the city | 3.8 | 0.60 | 3−5 | Internal |
| 19. Adaptation policies | 3.7 | 0.78 | 2−5 | External |
| City structure, development, and infrastructure | | | | |
| 20. Transport and accessibility | 4.2 | 0.60 | 3−5 | Internal |
| 21. Public sector as the driver of city development | 4 | 0.89 | 2−5 | Internal |
| 22. District (social inequality) | 4 | 0.77 | 3−5 | Internal |
| 23. City structure (densification vs. dispersion) | 3.9 | 0.83 | 2−5 | Internal |
| 24. Helsinki unification with Espoo/Vantaa (Metropolitan Area) | 3.9 | 0.83 | 3−5 | Internal |
| 25. Form and functioning of critical infrastructure (water, ICT, energy) | 3.9 | 1.14 | 2−5 | Internal |
| 26. Densification of residential areas within the current city borders | 3.8 | 0.75 | 2−5 | Internal |
| 27. Infrastructure modernization and reconstruction | 3.7 | 0.78 | 2−5 | Internal |
| 28. Citizens' demand for services development | 3.7 | 0.90 | 2−5 | Internal |
| 29. Private sector as the driver of the city development | 3.5 | 0.81 | 2−5 | Internal |
| Macro-context factors | | | | |
| 30. Climate change secondary effects (social, technological, political and economic changes as a result of climate change impacts, e.g. climate refugees) | 4.1 | 0.54 | 3−5 | External |
| 31. Climate change direct effects | 3.8 | 1.17 | 1−5 | External |
| 32. Global economy | 3.8 | 1.25 | 1−5 | External |
| 33. European integration (stronger or weaker) | 3.1 | 1.14 | 1−5 | External |

from the City of Helsinki environmental administration in a face-to-face meeting, as well as with an online questionnaire targeted to seven climate change and urban planning researchers from the University of Helsinki and Aalto University. The experts removed several drivers, while adding others to the list, the rationale being the suitability and relevance for the Helsinki context. After this step, we had a list of 33 drivers (see Supplementary materials 2 for the full lists after literature review and after expert elicitation).

In **Stage 2**, we constructed scenarios to account for a multitude of possible socio-economic developments to provide insights for decision-making and planning. The scenario stage was divided into two steps: ranking of the drivers and integration of the drivers into the socio-economic scenarios (Table 1). To enable the construction of comprehensible scenario narratives, we reduced the number of drivers with a web-based ranking questionnaire targeted to the adaptation working group of the City of Helsinki administration. From this step onwards, we engaged only practitioners and not researchers in the empirical data collection. We conducted the survey during 2–24 June 2017 and it was answered by ten respondents (response rate 41.7 %). The response rate is typical and representative enough for the surveys aimed at organizations (Baruch and Holtom, 2008). As a result of ranking, we selected the drivers with the top-5 average values (average score $\geq$3.9, see Table 3), as we wanted to cut the initial list of 33 drivers to a reasonable number of key drivers (most important ones), and at the same time include different types of drivers in the final list. The final list of ranked key drivers comprised of 12 drivers, which we then integrated into the local socio-economic scenarios developed in the Helsinki Master Plan process by the City administration.

In **Stage 3**, the goal was to map the spatial patterns of future vulnerability. In a participatory mapping workshop on November 1st, 2017, we asked eleven participants from the City of Helsinki administration to map the areas of possible vulnerability indicator changes based on the information from the scenarios that integrated the chosen variables from stage 2. In the workshop, we briefed the participants that the study will be used to assess future vulnerability. However, to avoid directing participants' responses, we did not refer to vulnerability in the SoftGIS questionnaire and focused the questions on changes in specific themes (e.g. infrastructure, housing pricing, development of new areas). We used expert opinion as in many conditions future-oriented data on vulnerability indicators is not available at a fine spatial resolution or is unreasonable to produce (Jurgilevich et al., 2017). The participants answered a SoftGIS survey (Table 2, full questionnaire is available in Supplementary materials 4) independently within the facilitated workshop setting. The discussion rounds were held after each scenario. In the survey, similar questions to the three scenarios were presented (Table 2), asking respondents to answer by marking relevant areas on the map with polygons. The obtained dataset comprised of 27 maps (3 scenarios × 9 vulnerability indicators). We constructed the questions on the basis of the vulnerability indicators and their proxies used in a previously published index-based assessment of current social vulnerability for the Helsinki Metropolitan Area (Kazmierczak, 2015). We built the survey around the two dimensions of vulnerability (enhanced exposure and adaptive capacity, Fig. 1). We excluded sensitivity since it pertains to personal factors (such as age, health status, education), for

**Table 4**
Summary of the scenarios and changes in key drivers.

| Key drivers | Scenario 1 Negative – slowing development – dispersed city structure | Scenario 2 Balanced – balanced growth of the region – multi-centered structure | Scenario 3 Fast – fast growth – dense mono-centered city |
|---|---|---|---|
| Economy (at the national level) | Economic decline | Steady and balanced economic growth | High and fast economic growth |
| Climate change impacts (incl. secondary effects) | - Sea level rise, intensifying heatwaves and floods<br>- Climate refugees from Helsinki and abroad | - Moderate direct climate change impacts<br>- Increase in number from climate refugees from abroad | - Direct impacts are minor and mainly favorable |
| Infrastructure | Critical infrastructure and residential areas require retrofitting and modernization | - Critical infrastructure is partially modernized<br>- Green infrastructure is under development; however, it is not seen as an essential part of critical infrastructure | - Critical infrastructure is fully modernized<br>- Green infrastructure is a part of critical infrastructure, providing natural drainage and cooling effect |
| Governance and environmental policies (incl. mitigation policies, public/private sector as city developer, national regulation) | - No investments in sustainability<br>- Greenhouse gas reduction goals are not achieved<br>- Private sector leads city development | - Sustainability is part of national economic development<br>- Government supports executive branches at the local level, however, decisions are made at the national level<br>- Public and private sectors steer the development of the city | - Sustainability is central to economic policies<br>- Helsinki population growth and densification pose challenges for sustainable city development<br>- Government pushes for sustainable development through legislation and supports implementation at the local level<br>- Public and private sectors steer the development of the city |
| Population (incl. migration, social inequality) | - Population growth in Helsinki slows down, but continues in the Metropolitan Area<br>- No new residential areas are built in Helsinki<br>- Social inequality deepens | - Helsinki population growth slows down slightly<br>- Population growth in the Metropolitan Area continues to be high<br>- Social inequality is present | - Population growth in Helsinki and in the Metropolitan Area is high<br>- Social inequality and segregation are a recognized issue but stays at the European (low) level |
| City structure (incl. transport and accessibility, unification with Metropolitan Area) | - Helsinki within its current borders<br>- Dispersed city structure, balanced development of the Metropolitan Area | Helsinki Metropolitan Area unites and builds a strong balanced regional development strategy | Helsinki is Finland's strong and dense center |

which it is not reasonable to produce datasets for medium-term future at fine spatial resolution (e.g., city district level).

In the map analysis, we first used qualitative directed approach (Hsieh and Shannon, 2005) to examine what kind of similarities and linkages there are between the identified key driver changes in the scenario narratives and spatial patterns in vulnerability indicator maps. Second, we analyzed the maps quantitatively to establish patterns of changes across indicators and across scenarios. To find statistically significant spatial clusters of likely changes, we conducted a Local Moran's I analysis (Anselin, 2010) of sum maps with fixed 500 m spatial neighborhood distance and a 95 % confidence level. We mapped high clusters including both High-High clusters of larger contiguous areas with likely changes and High-Low outliers denoting smaller areas of likely changes surrounded by areas with no likely changes. We calculated the pairwise similarity of binary indicator maps (i.e. areas in high clusters and areas not in high clusters) between different indicators within each scenario and between the same indicators across scenarios with Jaccard index (Jaccard, 1912).

## 3. Results

### 3.1. Drivers and scenarios

The final list of drivers of socio-economic and land use change in Helsinki up to 2050 includes 12 key drivers (Table 3). The drivers are clustered into the following categories: demographics, economy, governance, city structure, development and infrastructure, and macro-context factors, similarly to Bennett et al. (2016). These drivers are also divided into external (five drivers), internal (six drivers), and both internal and external (one driver). The starting point for the classification is the city level for internal drivers, and the sub-national, national, and international for external drivers (Leichenko and O'Brien, 2002; Luers, 2005). All the internal drivers fall into one category: "city structure, development, and infrastructure", while the external drivers fall into the categories "economy," "governance," and "macro-context factors". The driver "migration" from the category "demographics" is both external and internal (migration into Helsinki and out of Helsinki). The external drivers can also be divided by scale, with macro-context factors having international character, economy and governance national character, and migration both national and international character. Overall, there is moderate variation in answers. All the drivers are considered as "highly important" by at least one respondent. The highest variation is observed in macro-context drivers.

The key drivers were integrated into the Helsinki 2050 Master plan scenarios following the scenarios' logic (Table 4, Supplementary materials 3). The Master plan scenarios were developed in a participatory process by the city's planning department based on two main axes: city structure and economic/population growth pattern. Scenario 1 named "Negative: slowing development – dispersed city structure" explores the pathways in the situation of an economic decline internationally and locally as well as its consequences for the local demographics, economy and city maintenance. In this scenario, the urban planners develop a city with a dispersed structure, i.e., several centers of economic activity in addition to the city center. The economy is in recession and population is not growing in Helsinki. In Scenario 2 named "Balanced: balanced growth of the region – multi-centered structure", the city structure presupposes a balanced development of the capital region with strong centers in the Metropolitan Area, and global and Finnish economies are steadily growing. Scenario 3 named "Fast: fast growth – dense mono-centered city" features high economic and demographic growth and a strong mono-centered city structure.

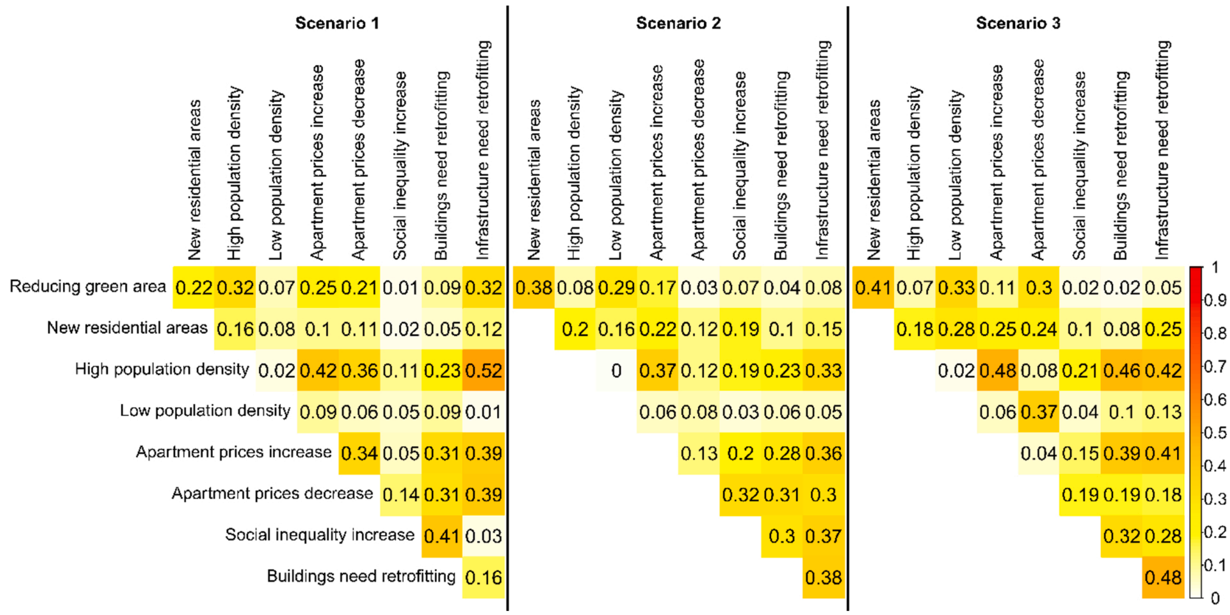


**Fig. 2.** Jaccard similarity between different indicators in each scenario. Scenario 1 is "Negative", Scenario 2 – "Balanced", Scenario 3 – "Fast".

### 3.2. Participatory mapping: changes in vulnerability dimensions

This sub-section presents changes in vulnerability dimensions (enhanced exposure, adaptive capacity) and corresponding indicators, based on the analysis of maps, scenarios, and similarities between the maps. The similarities between different indicators in the same scenario highlight the spatial overlaps of vulnerability indicators (Fig. 2), while the comparisons of the indicator maps between the scenarios indicate differences between the scenarios (Figs. 3–9).

#### 3.2.1. Changes in enhanced exposure

*3.2.1.1. Physical environment: reducing green areas and new residential areas.* In scenario 1, the key drivers show neither economic nor population growth, concentration of labor/employment opportunities along the main transportation pathways, possible migration of climate refugees to Helsinki, and a decrease in the attractiveness of coastal areas due to floods and sea-level rise. According to the map responses by the practitioners, scenario 1 shows a moderate reduction in green areas (Fig. 3), and a moderate increase in new residential areas, most of which are currently under construction (Fig. 4). Scenario 2 suggests a multi-centered city, and the maps show the development of residential and commercial areas in current suburban districts along the main transportation pathways (Fig. 4). Green areas are reducing in the same areas (Fig. 3), in addition to the areas marked in scenario 1. Scenario 3 features a mono-centered city with densified suburban areas and a need to develop areas of low density (Figs. 3 and 4). The analysis of maps and scenario narratives suggests that the reduction of green areas in Helsinki is strongly associated with urban growth mainly driven by population growth (both natural and due to migration), the state of the economy, and the labor market situation. This is supported by the Jaccard similarity analysis where reducing green areas are somewhat similar with the new residential areas in all scenarios, with the similarity growing from scenario 1 to scenario 3 (S1: 0.22; S2: 0.38; S3: 0.41; Fig. 2).

*3.2.1.2. Construction and infrastructure.* The state of residential stock and critical infrastructure is associated with the state of the economy, environmental policies in the city, and whether the public or private sector is the driver of city development and green infrastructure. According to the scenario 1 narrative, neither critical infrastructure nor

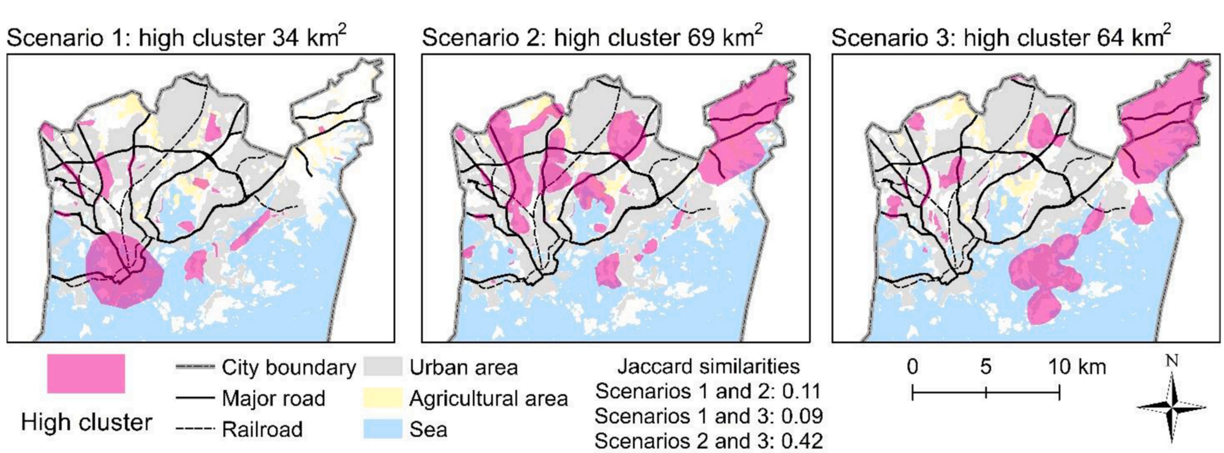


**Fig. 3.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 1: "According to the scenario X, can you mark the locations where the **green areas** may reduce significantly?". In addition, Jaccard similarities between maps and the size of high cluster area are shown.

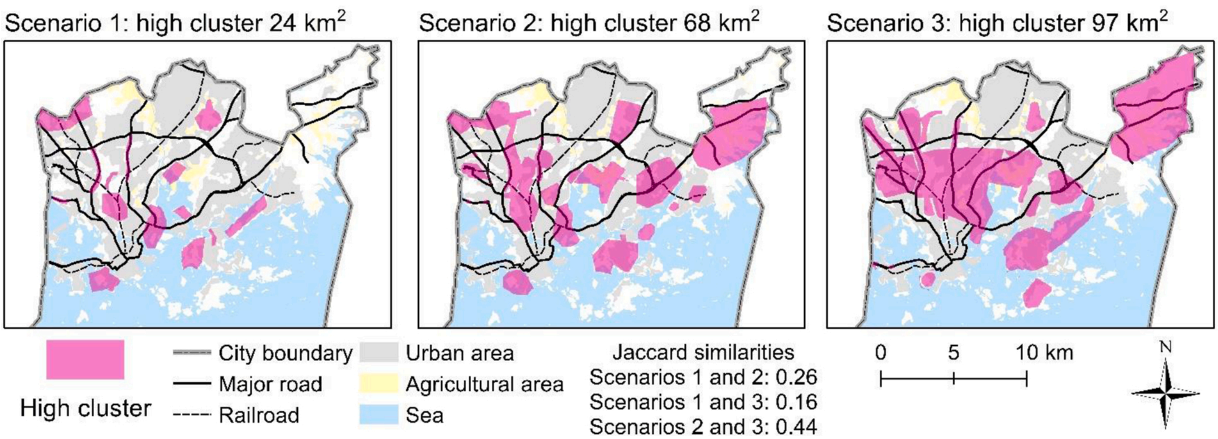


**Fig. 4.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 2: "According to the scenario X, can you mark the locations where **new residential areas** will be built?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

residential areas are modernized due to the economic decline, disregard of environmental policies and a lack of pressure to build or modernize/densify residential areas because of a decline in population growth. According to the scenario 1 map responses, almost all Helsinki residential areas require retrofitting (Fig. 5), while there are fewer areas needing retrofitting and fewer polygons drawn in the other two scenarios (Table S1). As for the critical infrastructure in need of modernization, large and relatively similar areas are mapped in scenarios 2 and 3, but there are fewer projected areas in the scenario 1 (Fig. 6). Additionally, there are similarities in the areas with high population density and the need to modernize critical infrastructure within the scenarios (S1: 0.52; S2: 0.33; S3: 0.42; Fig. 2). This implies a larger concentration of people with an increased vulnerability due to the decaying infrastructure.

### 3.2.2. Changes in adaptive capacity

*3.2.2.1. Occupancy: population density.* High population density areas are related to the increase in new inhabitants (e.g., in the cases of new densely built residential areas) or to a steady high number of inhabitants, as well as to types of residential buildings (e.g., typically multistory apartment buildings). In the scenario narratives, population density is related to migration and population growth, city structure, Helsinki unification with the Metropolitan Area, and transport and accessibility, among others. Predictably, the city center (located in the southwest corner of the maps) is marked to remain the most densely populated in all scenarios (Fig. 7). Respondents have also drawn further densification along the major transportation lines especially in scenario 2. Additionally, further densification is mapped all over eastern and northern Helsinki in scenario 3. Overall, areas with high population density show high similarity between different scenarios and the largest increase is projected for scenario 3 (Fig. 7).

*3.2.2.2. Economic and social inequality: apartment pricing and social inequality.* Apartment pricing, as an income proxy, is influenced by a range of macroeconomic and local factors, including the key drivers identified in this study: migration and population growth, the state of the economy, public or private sector as city developers, city structure, transport and accessibility, social inequality, and distribution of workplaces. Overall, the areas with a projected apartment price increase are relatively similar across the scenarios, although larger areas of an apartment price increase are drawn in scenarios 2 and 3 compared to scenario 1 (Fig. 8). Moreover, the mapping results suggest an increase in prices across all scenarios in the traditionally more expensive city center and in northern suburban Helsinki (Fig. 8). In scenario 2, the growth of prices is marked along the major transportation lines. In scenario 3, growth in prices is drawn all around Helsinki and is condensed. This is due to high demand in Helsinki, a mono-centered structure, population growth, and the concentration of working places in Helsinki rather than in the Metropolitan Area, as also the scenario narrative suggests.

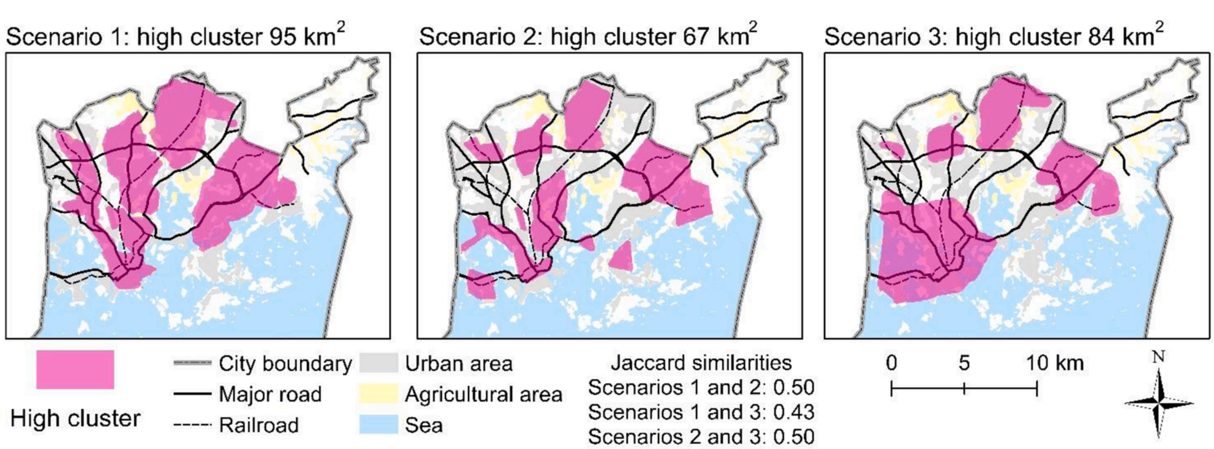


**Fig. 5.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 3: "According to scenario X, can you mark the areas where **residential buildings** are getting old and need retrofitting?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

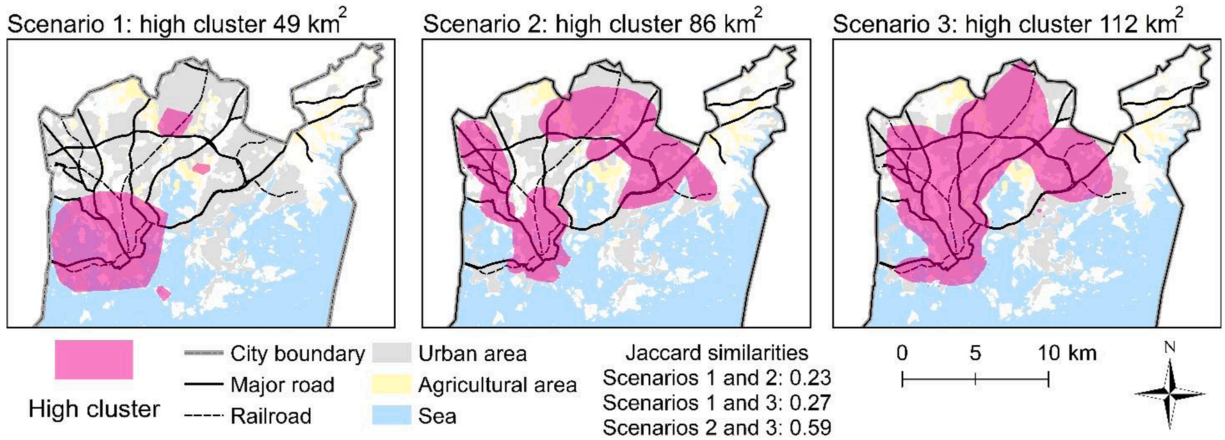


**Fig. 6.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 4: "According to scenario X, can you mark the areas where **critical infrastructure** (energy, water, etc.) is getting old and needs modernizing?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

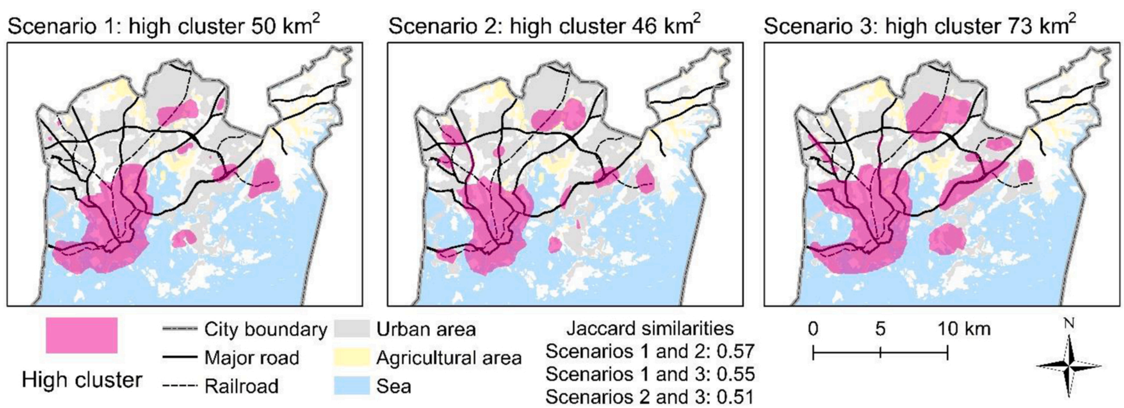


**Fig. 7.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 5: "According to scenario X, can you mark the areas where **population density will be high**?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

Social inequality is influenced, for example, by migration in Helsinki, the state of the economy, urban planning, and social policies. Especially in scenario 1, the respondents project a further deepening of social inequality in areas that are currently considered to be socially segregated, for example, eastern Helsinki, and there is high similarity in the areas where social inequality may increase between the scenarios (Fig. 9).

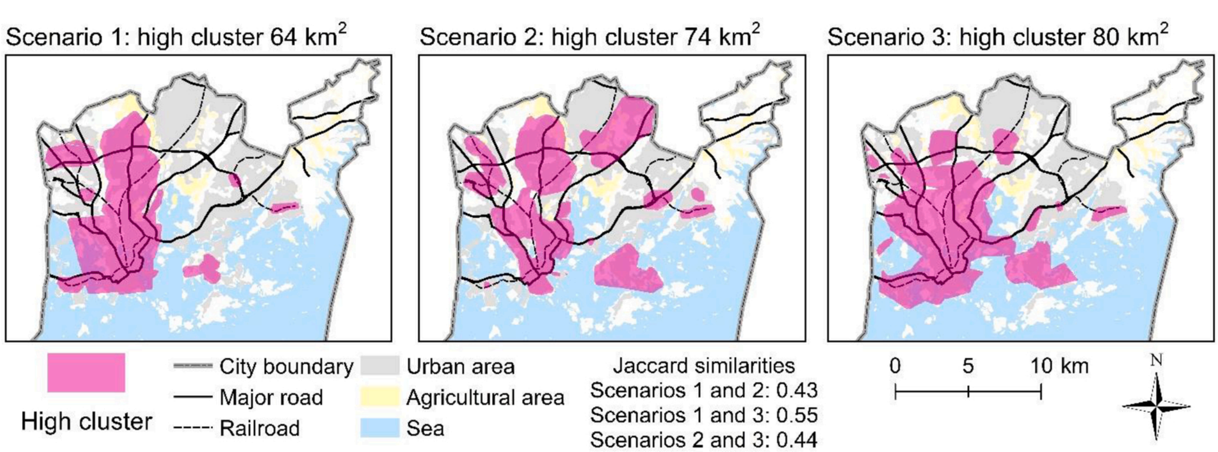


**Fig. 8.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 7: "According to scenario X, can you mark the areas where the **housing prices may increase** significantly?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

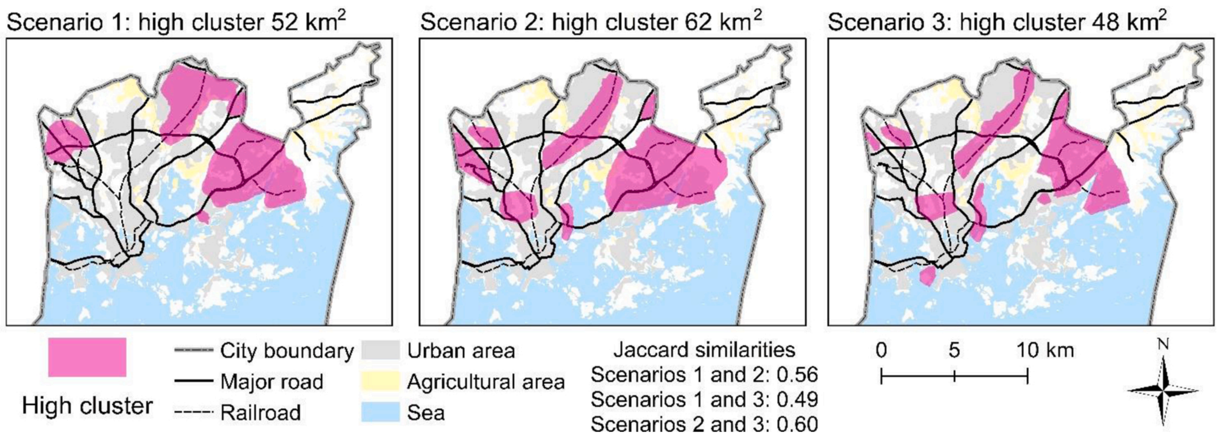


**Fig. 9.** Local Moran's I high clusters (both High-High and High-Low) with 0.95 confidence level, based on answers on SoftGIS survey question 9: "According to scenario X, can you mark the areas where **social inequality** may increase significantly?" In addition, Jaccard similarities between maps and the size of high cluster area are shown.

### *3.3. Vulnerability development pathways and implications for urban policy and planning*

In this section we connect the scenario narratives, changes in key drivers and changes in vulnerability according to the indicator maps in Section 3.2. As a result, we present vulnerability development pathways based on the scenarios and practitioners' opinion of how vulnerability indicators may change according to these scenarios.

In the "Negative" scenario 1, economy decline is the main driver of vulnerability and affects multiple aspects of vulnerability, showing direct, indirect, and cascading effects. First, it has a *direct* negative impact on citizens' income; thus, it reduces their ability to prepare to climate change related risks by e.g., investing in structural modifications, as well as hampers their capacity to respond and recover (Fig. 1, Table 2). Second, it has *indirect* effects on citizens' vulnerability by hindering city's capacity to modernize critical infrastructure and retrofit residential areas, thus increasing citizens' enhanced exposure to negative impacts of floods and heat waves (Fig. 1, Table 2). Third, the scenario suggests that sustainable planning is disregarded due to the recession and has an ad hoc and fragmented character. According to the scenario narrative, the economic recession has a *cascading effect* on sustainable planning by shifting the governance and policy priorities, and thus creating challenges for preventative retrofitting of infrastructure and residential stock. In the maps, there is strong similarity between the areas of high population density and areas where critical infrastructure needs to be modernized (0.52, Fig. 2), which suggests a greater concentration of people with potentially increased vulnerability. Fourth, according to the scenario narrative, social inequality deepens. As indicator maps suggest, it is concentrated in eastern and northern Helsinki and has relatively high spatial similarity with areas where residential buildings need retrofitting (0.41, Fig. 2), which increases two vulnerability dimensions (i.e., adaptive capacity and enhanced exposure, Fig. 1 and Table 2). These changes have implications for social and healthcare sectors of urban planning, as well as for housing, safety and rescue services, since people from lower income categories or socially segregated areas have a reduced ability to invest in structural modifications to prepare to heatwaves and floods and a lower capacity to recover from such events (Table 2). This means that social and healthcare services need to increase response capacity in these city areas in cases of heat or flood events, as well as increase prevention efforts before heatwaves and flood events. Finally, this scenario features a few changes that have positive effects on vulnerability. More specifically, low population growth and dispersed city structure do not assert high pressure to densify the areas, which in its turn helps to preserve green infrastructure (Figs. 3 and 4), reducing enhanced exposure.

In the "Balanced" scenario 2, the main drivers of vulnerability are related to population growth and migration combined with the fragmented character of environmental policies and sustainable planning. The scenario features the city structure with strong multiple sub-centers creating a balanced population distribution and densification (Fig. 5). At the same time, decrease in green space as shown in the indicator maps (Fig. 3), exacerbated by the neglect of green infrastructure in construction as per the scenario narrative, increases enhanced exposure and risks related to heat and pluvial flooding (Table 2). According to the scenario, the multi-centered structure drives the densification along major transportation lines, and there is relatively high similarity between the maps of reducing green areas and new residential areas especially in these areas (0.38, Fig. 2). For current urban planning, this highlights the need to design new residential areas or densify so that the green infrastructure partly compensates for the loss of existing green areas. Other potential increases in vulnerability are linked to increases in social inequality and areas where residential stock and critical infrastructure require retrofitting. These areas have partly similar spatial patterns (0.30−0.38, Fig. 2) indicating a spatial overlap in two vulnerability dimensions for residents, i.e., adaptive capacity and enhanced exposure (Table 2 and Fig. 1). While the maps suggest deepening of social inequality in eastern and northern Helsinki, retrofitting needs are projected to increase also in the city center. This should be considered in planning by social and healthcare services as well as infrastructure and housing departments. Nevertheless, the scenario highlights that the state of economy has positive effects on vulnerability as critical infrastructure and residential stock are at least partially retrofitted to withstand direct climate impacts, reducing residents' enhanced exposure (Table 2).

The "Fast" scenario 3 covers changes in drivers that overall decrease the population's vulnerability: fast economic growth improving citizens' financial situation and their capacity to prepare, respond, and recover, as well as city's capacity to invest in full modernization of critical infrastructure, and retrofitting of residential areas (Fig. 1 and Table 2). However, a mono-centered structure and high population and economic growth featured in this scenario drive the development of new areas and densification all over Helsinki (Figs. 4 and 7) at a loss of green areas (Fig. 3). The population density maps, as well as the map of new development areas confirm the mono-centered city structure. Maps show similarity between the loss of green areas and new residential areas (0.41) implying that the development of new residential areas can occur in the suburban areas at a loss of green space. These trends increase enhanced exposure and decrease population's capacity to respond, however, in this scenario, these risks are set off by the central role given to green infrastructure, which becomes a part of critical infrastructure. Overall, the scenario narrative underscores that high and fast population and economic growth together with high urbanization and densification can pose challenges to sustainable urban planning. The similarities between high population density, retrofitting needs and aging critical infrastructure observed in maps (similarities between 0.42 and 0.48, Fig. 2) highlight the need for strong implementation of sustainable planning and environmental policies, as well as timely upgrading of the infrastructure and residential stock. Also, in this scenario, climate risks may increase, and particular attention should be paid to infrastructure modernization in the city center, as well as to the prevention, response, and recovery capacity in the most densely populated areas.

## 4. Discussion

Our study responds to several research gaps in vulnerability assessment scholarship. First, it addresses the need for methodological advances to capture the dynamics of vulnerability and system complexity (de Sherbinin et al., 2019; Ford et al., 2018; Jurgilevich et al., 2017; Adger et al., 2018). We do that by integrating socio-economic scenarios and vulnerability mapping. The use of mixed methods enables to enrich the data and expand the study, as well as to analyse the unconventional dataset obtained during a participatory mapping workshop (Johnson, 2011; Greene et al., 1989; Sechrest and Sidani, 1995). As a result, mixing qualitative, quantitative, and participatory methods in data collection, as well as integrating qualitative and quantitative methods in data analysis allows us to explore vulnerability dynamics as a process, tracing pathways of its development, establishing links between drivers and changes, as well as identifying spatial patterns.

Second, our study enhances the understanding of vulnerability, its causes, and its formation as a process by identifying the drivers, direct, indirect, and cascading effects on vulnerability and visualizing vulnerability changes spatially. This differs from most assessments that use trend extrapolations (Ford et al., 2018; Jurgilevich et al., 2017; de Sherbinin et al., 2019). Our results, based on experts' judgement, show that the drivers are in a constant dynamic interaction with each other, and that the impacts on vulnerability can be direct, indirect and cascading, and outcomes can vary, as was previously suggested in literature (Oppenheimer et al., 2014; Bennett et al., 2016; Räsänen et al., 2016; Ruth and Coelho, 2007). For example, in the case of Helsinki, state of the economy influences labor market and location and distribution of workplaces and subsequently population growth in the city, which according to the practitioners' responses, has subsequent impacts on population density, city structure and green areas influencing future vulnerability. At the same time, the state of the economy has impacts both on the ability of the city to maintain critical infrastructure and to retrofit the residential stock, and on the citizens' ability to prepare, respond and recover from climate change impacts. These drivers and developments are often context-specific; thus, they require the use of local scenarios and benefit from the engagement of stakeholders. Therefore, additional case studies exploring vulnerability dynamics could advance the field by establishing patterns of drivers, their interactions and vulnerability changes.

Third, we respond to the need to account for cross-scale interactions by placing cities in a national and international context (Ford et al., 2018). Key drivers at the city, national and macro-context levels provide information for preventative urban planning and proactive adaptation (Vervoort and Gupta, 2018; Quay, 2010). More specifically, while a city can manage and account for drivers at the city level in their planning (such as e.g., transportation, city structure), planning adaptation under the influence of drivers at macro levels (e.g., national legislation and regulation, or climate change secondary effects) is dependent on the city capacity, governance system and mechanisms for adaptation mainstreaming. While the analysis of the connections between the levels of drivers and adaptation/planning responses was not the scope of this study, we propose this as a possible area for future research. Studying the proactive and reactive responses in conjunction with the vulnerability drivers, as well as the levels of drivers in conjunction with steering and mainstreaming adaptation and planning actions, could be beneficial for the conceptual understanding of adaptation planning and its subsequent implementation. More specifically, this is pertinent from the perspective of vertical adaptation mainstreaming (Rauken et al., 2015), and may contribute to a better uptake of the assessment results, currently noted as unsatisfactory (Ford et al., 2018).

### 4.1. Limitations of the study and ways forward

There are shortcomings with any chosen methodology, in our case, some of these are related to the use of expert judgement and its reliability. We purposefully used the expert opinion in all the empirical parts of the study to a) tailor the assessment to the local context, b) utilize local in-depth knowledge, and c) increase the relevance of the results for the local decision-making (Salter et al., 2010). The research question of exploring urban futures did not require a higher level of stakeholder participation, as it did not require solving complex problems (Hurlbert and Gupta, 2015). Thus, we involved participants within a "contractual" participatory mode: limited to the data collection, while the study framework, methodology, and results' interpretation were carried out by the researchers involved in the study (Probst and Hagmann, 2003; Barreteau et al., 2010). Additionally, as with any method involving stakeholder participation, the data and results depend on the stakeholder composition. In this study, we engaged mainly practitioners form the city administration, and relied on the scenarios developed by the city administration. The rationale for that is that the practitioners possess the best knowledge available concerning the city's development trajectories. We included as large set of administration departments as possible to diversify the representation and to cover the city development to the fullest degree. However, we acknowledge the risk of relying heavily on the participation of practitioners and a possibility of missing important information.

We did not present the study through the vulnerability and risk lens to the participants to avoid bias and risk framing in the data collection; on the contrary, we framed the study for the participants as the exploration of Helsinki's futures. In the following steps of the study, utilizing the obtained results in adaptation and urban planning would require a higher level of participation, e.g. "collaborative" or "collegiate" (Hurlbert and Gupta, 2015; Barreteau et al., 2010; Probst and Hagmann, 2003), and special attention should be paid to reduce bias. Overall, we do not see the reliance on expert judgement as a disadvantage; however, the results should be treated as a reflection of experts' informed anticipation (Salter et al., 2010), and differently from e.g. assessments using statistical projections.

Another limitation is inherent to the use of scenarios. As any futures research, this study is empirical but non-evidential and cannot be validated, and thus should be treated as such – not as projections or forecasts of futures but rather different pathways of how future may develop in order to use these insights in current planning, as action research should be used (Voros, 2007). The results of such research should be used in anticipatory governance (Quay, 2010; Vervoort and Gupta, 2018; Jurgilevich, 2021), or more specifically, in flexible adaptation and planning including no-regret or worst case strategies, robust actions, and contingency plans (Quay, 2010).

We observed some inconsistencies in the answers to SoftGIS questionnaire. For example, in question 9 (critical infrastructure in need of modernization, Fig. 7), the respondents marked larger areas and more polygons in scenarios 2 and 3 than in scenario 1, whereas according to the scenario narratives, the need to modernize critical infrastructure was higher in scenario 1. These illogicalities were probably caused by diverging opinions among the respondents and by uncertainty in forecasting. Moreover, the number of polygons drawn for each question and each scenario varied significantly. This can depend on several factors, such as difficulty of the question and expertise of the respondents (answering to questions was not mandatory to avoid forcing the answers where respondent's expertise was insufficient). Additionally, time constraints and fatigue from answering the questionnaire may have also played a role; for example, the first questions received smaller and more precise markings, while some markings in the last questions encompass all Helsinki. In their post-workshop feedback survey (see Supplementary materials 5), the respondents mentioned that the questionnaires and marking responses were rather demanding and laborious.

The establishment of a threshold for key driver selection done subjectively by the researchers can possibly lead to the exclusion of important drivers or the inclusion of less important ones. This is particularly relevant when the number of ranking responses is low, and the differences are marginal. For example, if we had decided to set the threshold $\geq$4 in the driver ranking, "economy" drivers would have been excluded from the final list. Possibly, this problem can be balanced by including a larger pool of respondents or a stakeholder workshop to design the list of drivers. We shortened the list of drivers to make it and scenario narratives comprehensible for the SoftGIS workshop.

## 5. Conclusion

We develop a novel mixed methods approach to explore the dynamics of vulnerability in urban areas as a process by combining scenarios with participatory mapping. Our results in Helsinki show a multitude of interdependent drivers of vulnerability at multiple scales. The key drivers of vulnerability differ but similar mechanisms can be observed between the scenarios. In the "Negative" scenario, economic decline affects directly citizens' financial situation and capacity to prepare, respond and recover, and indirectly citizens' enhanced exposure by influencing city's financial capacity to upkeep residential stock and critical infrastructure. In the "Balanced" scenario, the densifying city structure and new residential areas reduce green space, while critical infrastructure and residential stock are partially modernized and retrofitted. To avoid increased vulnerability, sustainable and climate-proof policy and planning need to be prioritized. In the "Fast" scenario, the main drivers of vulnerability are related to high levels of densification, which similarly to the balanced scenario, comes at a cost of green areas. However, high economic growth has a positive impact on citizens' and city's financial situation, infrastructure is modernized, residential stock is retrofitted and sustainable and climate-proof planning are central.

The study provides a conceptual contribution to climate change vulnerability and adaptation literature by showing the dynamic and complex nature of vulnerability as a phenomenon. It shows possible indirect and cascading effects of socio-economic changes and planning and policy decisions on future vulnerability, highlighting the need to account for vulnerability dynamics in current adaptation policy and urban planning. Practitioners can use the developed methodology and results as the first step in anticipatory adaptation governance, for example, when developing no-regret, worst case or flexible urban development strategies. Accounting for vulnerability dynamics in the assessments can also contribute to prevent maladaptation as well as adjust current policy and planning directions to reduce vulnerability increase.

Finally, the usability and usefulness of vulnerability assessments conducted with qualitative and participatory approaches should be further examined. We suggest that more urban level studies should be carried out to explore the links between socio-economic development, urban planning and future vulnerability, focusing on the establishment of driver change patterns, driver interactions and vulnerability changes. An important issue for further study is how to integrate this type of information into urban planning and adaptation governance.

## Author statement

Alexandra Jurgilevich: conceptualization, methodology, investigation, writing – original draft, writing – review and editing, project administration, funding acquisition.

Aleksi Räsänen: formal analysis, data curation, writing – original draft, writing – review and editing, visualization, supervision.

Sirkku Juhola: investigation, writing – original draft, writing – review and editing, supervision.

## Declaration of Competing Interest

The authors declare no conflict of interest.


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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.08.002.

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