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Extending the Shared Socioeconomic Pathways at the City Scale to Inform Future Vulnerability Assessments — The Case of Boston, Massachusetts

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Climate change will impact cities' infrastructure and urban dwellers, who often show differentiated capacity to cope with climate-related hazards. The Shared Socioeconomic Pathways (SSPs) are part of an emerging research field which uses global socioeconomic and climate scenarios, developed by the climate change research community, to explore how different socioeconomic pathways will influence future society's ability to cope with climate change. While the SSPs have been extensively used at the global scale, their use at the local and urban scale has remained rare, as they first need to be contextualized and extended for the particular place of interest. In this study, we present and apply a method to develop multi-scale extended SSPs at the city and neighborhood scale. Using Boston, Massachusetts, as a case study, we combined scenario matching, experts' elicitation, and participatory processes to contextualize and make the global SSPs relevant at the urban scale. We subsequently employed the extended SSPs to explore future neighborhood-level vulnerability to extreme heat under multiple plausible socioeconomic trajectories, highlighting the usefulness of extended SSPs in informing future vulnerability assessments. The large differences in outcomes hint at the enormous potential of risk reduction that social and urban planning policies could trigger in the next decades.

Keywords: Scenarios; vulnerability; extreme heat; shared socioeconomic pathways; Boston.

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1. Introduction

Global climate change will affect cities worldwide (Romero Lankao and Qin 2011), with a wide range of impacts on cities' infrastructure and urban dwellers (Revi *et al.* 2014). Ways in which climate-related hazards — such as flooding, droughts, and heat waves (Guerreiro *et al.* 2018) — will affect urban areas has been well-documented by the climate Impacts, Adaptation, and Vulnerability (IAV) research community over the past decades. A substantial part of the existing literature has also been dedicated to understanding the differential vulnerability of urban population to climate-related hazards (Cooley *et al.* 2012; Garschagen and Romero-Lankao 2013; de Sherbinin and Bardy 2016; Kashem *et al.* 2016). However, very little is known about ways in which socioeconomic development and demographic change will influence future vulnerability to climate-related hazards (Rohat 2018; de Sherbinin *et al.* 2019). Up until recently, most assessments of future urban climate risks typically projected the effects of various climate change scenarios under current socioeconomic conditions (Birkmann *et al.* 2013). Neglecting the role of socioeconomic development in shaping future vulnerability and climate risks is problematic because it creates a systematic bias in climate adaptation decision-making. This bias results in the overestimation of the impacts of climate change and the underestimation of the role of socioeconomic development for future vulnerability and climate related risks (Ebi *et al.* 2016).

Partly to address this issue, the climate change research community developed a new scenario framework, made of climate change scenarios (RCPs — Representative Concentration Pathways; Van Vuuren *et al.* 2011) and socioeconomic scenarios (SSPs — Shared Socioeconomic Pathways; O'Neill *et al.* 2017) developed in parallel. While RCPs depict potential trends in atmospheric concentrations of greenhouse gases (Van Vuuren *et al.* 2011), SSPs are a set of five global socioeconomic development narratives, organized along different combinations of challenges to adaptation and mitigation, as shown in Figure 1 (see O'Neill *et al.* 2017). SSPs and RCPs are combined to produce integrated climatic and socioeconomic scenarios, which allows the analysis of a range of potential outcomes having different implications for vulnerability, risk, adaptation, and mitigation (Van Vuuren *et al.* 2014). Consequently, SSPs have the potential to foster the integration of socioeconomic projections in IAV research (Kriegler *et al.* 2012). The global narratives, detailed in O'Neill *et al.* (2017), have been complemented with country-level quantifications for key indicators such as population, education (KC and Lutz 2014), urbanization (Jiang and O'Neill 2017), rate of technological development, and economic growth (Crespo Cuaresma 2017). Since the SSPs are

Figure 1. The Five SSPs and their Challenges for Adaptation and Mitigation (O'Neill *et al.* 2017)

designed as global development trends, they need to be contextualized (or "extended") to be used in sectoral (e.g., health or urbanization) or local research (Van Ruijven *et al.* 2014) as in the below examples. Sectoral extensions and quantifications of the global SSP narratives (O'Neill *et al.* 2017) have flourished, e.g., extended SSPs for health (Ebi 2013; Sellers and Ebi 2017), food security worldwide (Hasegawa *et al.* 2015), the water sector (Wada *et al.* 2016; Yao *et al.* 2017), fisheries (Maury *et al.* 2017), forestry (Kemp-Benedict *et al.* 2014), population distribution (Jones and O'Neill 2016), and urbanization (Li *et al.* 2019). However, there have been only a few regional extensions, including extended SSPs for the Barents Region (Nilsson *et al.* 2017), the South-East US (Absar and Preston 2015), West-Africa (Palazzo *et al.* 2017), New Zealand (Frame *et al.* 2018), the Mediterranean coast (Reimann *et al.* 2018), the Baltic Sea (Zandersen *et al.* 2019), Europe (Kok *et al.* 2019; Rohat *et al.* 2018), Tokyo (Kamei *et al.* 2016), and Houston (Rohat *et al.* 2019b). The latter extended SSPs — which are the only existing urban extended SSPs to our knowledge — have been developed based on the review of historical trends, and subsequently refined through an interactive process with key local experts using individual interviews and/or questionnaires.

Using the City of Boston, Massachusetts as a case study, we build upon these efforts and present an approach to develop extended SSPs at both the city and neighborhood-scale that are locally relevant while connected to the global SSPs framework. Additionally, we demonstrate how extended urban SSPs can be useful tools to explore future vulnerability in cities and inform future urban climate risk assessments by using our extended SSPs to assess future vulnerability to extreme heat in two Boston neighborhoods. This paper is structured as follows. We first introduce the case study and detail the methods employed to extend the global

SSPs. We then present the citywide and neighborhood-focused extended SSPs and provide an overview of a qualitative assessment of future vulnerability to extreme heat under each extended SSP. We conclude with a reflection on the suitability of the SSPs framework for climate risk assessments at the urban scale and provide suggestions for further research.

2. Study Area

The City of Boston, located on the East coast of the US, is the capital of the Commonwealth of Massachusetts and hosts ∼700'000 inhabitants (U.S. Census Bureau 2018). Boston has a strong economy — with major industries in health care and professional, scientific, and technical services — and one of the lowest unemployment rates in the country (BPDA 2017). The city's workforce relies on international immigration, with 28% of its total employment being foreign-born, making its economy susceptible to federal immigration policies (BPDA 2019). Boston is also characterized by important and increasing socioeconomic and racial inequalities, with 18% of its residents living below the poverty level. While among Whites the poverty rate is around 12%, it is at 21% among Black/African–American residents, 25% for Asian residents, and 28% for Hispanic/Latino residents (U.S. Census Bureau 2018). Inequalities, ageing infrastructure, and rising costs of real estate pose significant challenges to Bostonians' capacity to adapt to stresses and shocks, such as climate-related hazards (BRC 2016).

Extreme heat is one of the main climatic threats in Boston, with climate change leading to more frequent, more intense, and longer heat waves (Douglas *et al.* 2016), which are exacerbated by the urban heat island (UHI) effect. The presence of green infrastructure, such as green spaces and trees, in urban areas can help mitigate the UHI effect, making its presence and distribution a key factor influencing residents' vulnerability to extreme heat (Street *et al.* 2013; Coutts *et al.* 2015; Melaas *et al.* 2016). The City of Boston's climate change vulnerability assessment (City of Boston 2016) predicts climate change will triple the annual heat-related deaths by 2050 and will potentially lead to failures of critical infrastructure, such as transportation and energy systems. The city-wide vulnerability assessment also recognizes differentiated vulnerability within its population, with older adults, children, people with health conditions, people of color, people with low- to no-income, and people with limited English proficiency considered to be particularly vulnerable (City of Boston 2016).

In this study, we focus on two adjacent neighborhoods, namely, Jamaica Plain and Roxbury (Figure 2). Jamaica Plain and Roxbury have considerably different demographics. In Jamaica Plain, approximately 56% of the population is White,

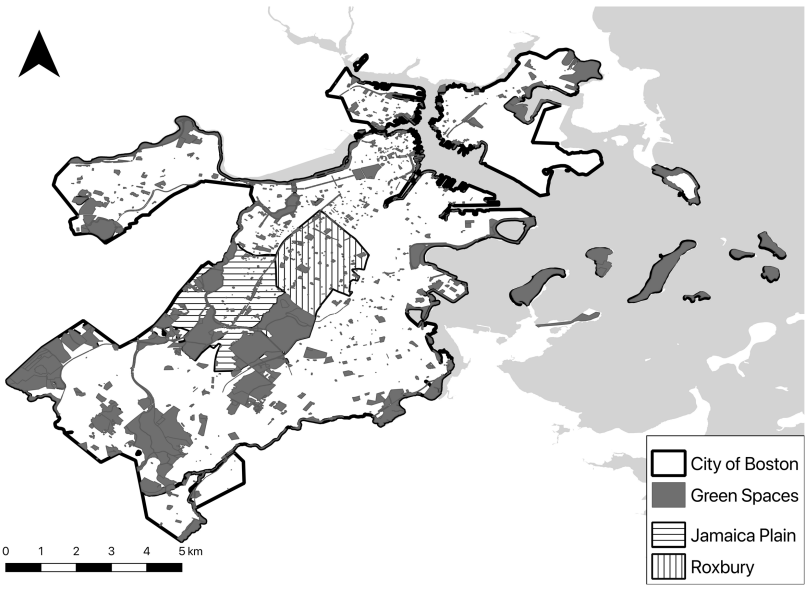

Figure 2. Case Study Neighborhoods and Green Spaces in the City of Boston (Eastern United States)

25% is Hispanic, and 10% is Black/African–American. In Roxbury, approximately 53% of the population is Black/African–American, 29% is Hispanic, and 11% is White. In Jamaica Plain, the poverty rate is approximately 16%, while in Roxbury, it is 36% (BPDA 2018). These adjacent neighborhoods house low-income and high-income communities in close proximity to each other and together, represent racially/ethnically diverse populations. These characteristics render it particularly relevant to explore the differentiated vulnerability of populations exposed to similar local environments and climate-related hazards.

3. Methods

We developed and applied a three-step workflow (Figure 3) to extend the global SSPs at both the city- and neighborhood-level. We first matched the global SSPs with existing local scenarios, then used experts' elicitation to define city-wide extended SSPs, and finally used participatory processes to contextualize and extend the city-wide SSPs at the neighborhood-level. The participatory processes were also instrumental in identifying local drivers of vulnerability, which were used to assess future vulnerability to extreme heat under the neighborhood-level extended SSPs. Given the importance of socioeconomic inequalities at the local scale and its relevance for assessing vulnerability to extreme heat, we chose to

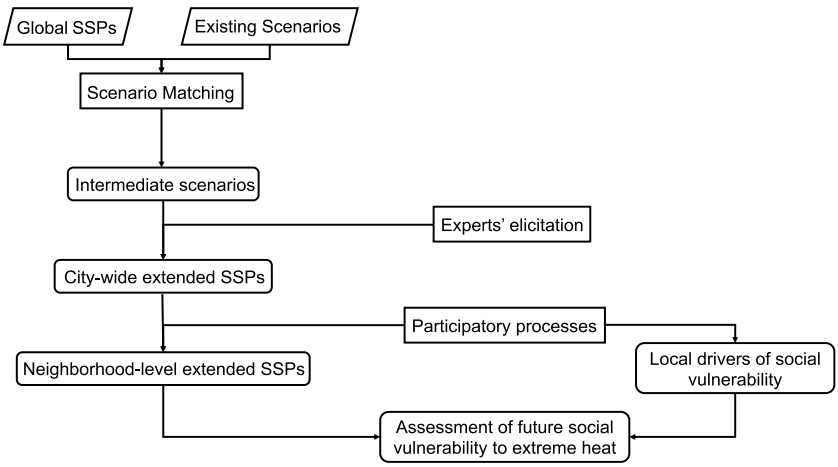

Figure 3. Workflow for Extending the Global SSPs at the City- and Neighborhood-levels. Existing Scenarios Shown in Rhomboids, Methods are Shown in Rectangles, and Outputs are Shown in Rounded Rectangles

focus on three SSPs that predict contrasted outcomes for socioeconomic inequalities and adaptation capacities, namely SSP1 (Sustainability), SSP2 (Middle-of-the-Road), and SSP4 (Inequality). SSP1 is defined as a scenario favoring sustainability and increased adaptation capacities, with decreased socioeconomic inequalities and increased investments in health and education, while SSP4 describes a future with increased inequalities and stratification, with differentiated access to health care and education, and depicts high challenges to adaptation. SSP2 represents the middle-of-the-road with a continuation of current trends, persistence of existing socioeconomic inequalities, and moderate challenges to adaption. Although SSP3 (Regional Rivalry) and SSP5 (Fossil-fueled Development) also have important implications for socioeconomic inequalities and adaptation capacities, they both narrate high challenges to mitigation. Instead, we chose to focus on SSPs that present varying levels of challenges to adaptation in order to assess vulnerability. Moreover, extending the five SSPs at the local level would likely result in redundancies and would complicate participatory processes. While the SSPs also present varying levels of challenges to mitigation, we focus on challenges to adaptation and their implications for vulnerability, and more specifically, vulnerability to extreme heat.

While the global SSPs are meant to reach the end of the century, future socioeconomic development is characterized by high uncertainty and such a timeframe would likely be difficult to integrate into local policy perspectives. Additionally, during participatory processes, it may be easier for actors,

stakeholders, and experts, to project forward one or two decades rather than to the end of the century. Therefore, the extended SSPs were developed up to 2040, following global and local narratives up to that point.

3.1. *Scenario matching*

The use of existing scenarios, that have been previously developed for a similar research sector and/or scale, as a starting point to develop new scenario narratives — instead of starting from scratch — is a common practice in scenario development. A few studies extending the global SSPs have used this approach (Kemp-Benedict *et al.* 2014; Absar and Preston 2015; Kok *et al.* 2019; Rohat *et al.* 2018). Methods to match scenarios from different sets of scenarios (e.g., matching the global SSPs to local socioeconomic scenarios) include the classification around two axes (Busch 2006; Kok *et al.* 2013), the classification by archetypes (Hunt *et al.* 2012; Van Vuuren and Carter 2013), and the comprehensive matching of each narratives' assumptions (Kok *et al.* 2019; Palazzo *et al.* 2017; Rohat *et al.* 2018). In this study, we used the latter to match the global SSPs to local scenarios developed by the Metropolitan Area Planning Council (MAPC), the local planning agency for Metropolitan Boston. The MAPC developed these scenarios along with academic experts, regional planning authorities, local municipalities, and state agencies, with the objective to predict demographic growth and housing demand in Boston's Metropolitan area (MAPC 2014). While these scenarios were not designed to predict future trends in climate change adaptation capacities or socioeconomic inequalities, they address broader socioeconomic development trends relevant to the SSPs. The MAPC developed two different scenarios, namely *Status Quo* and *Stronger Region*, which depict future socioeconomic and urban development in Boston up to 2040. Each of the MAPC scenarios was matched to an SSP who shared similar narratives and projections, particularly regarding population growth, economic development, and socioeconomic inequalities. For example, SSP1 and *Stronger Region* share similar projections, such as depicting higher levels of population and economic growth (in comparison to *Status Quo* or SSP2). By comprehensively matching narratives from the MAPC scenarios to the SSPs, "intermediate scenarios" were developed (see Figure 3). These "intermediate scenarios" serve as a local interpretation of the global SSPs and provides a frame of reference to guide the experts' elicitation process and the development of more detailed socioeconomic scenarios for the City of Boston.

As it is often the case at the city-scale, contrasted socioeconomic development scenarios are scarce. To our knowledge, the MAPC scenarios are the only

comprehensive socioeconomic and urban development scenarios available for the City of Boston. The MAPC scenarios and the SSPs have been quantified for key socioeconomic variables (e.g., population growth and economic growth). However, we relied on qualitative aspects of the scenarios, such as narratives predicting higher/lower economic growth, for their matching. Narratives can cover a larger range of domains than quantified projections, especially at finer spatial scales where quantified projections can be more difficult to obtain. For example, SSP1 depicts a pathway with decreasing inequalities, but quantified projections of this trend are difficult to obtain at a city or neighborhood scale.

3.2. *Experts' elicitation*

We followed the stepwise approach described in Knol *et al.* (2010) and conducted in-person semi-structured interviews (ranging from one to two hours) with eight selected experts with a deep understanding of the local context and dynamics. The interviews included two experts working on scenario development at the MAPC, three socioeconomic, housing, and demographic experts working at the Boston Planning and Development Agency, two public health experts with academic backgrounds, and one public health expert working for the Boston Public Health Commission. Experts were presented with a synthesis of the global SSPs and the intermediate scenarios, and were then asked to identify important drivers (and uncertainties) of local socioeconomic and urban development. They were asked to provide qualitative assumptions for each driver under each extended SSP, for 2040. Combining experts' opinions and assumptions with the intermediate scenarios, we constructed the city-wide extended SSPs. Although it could have been beneficial to include more experts in this process, it was chosen to conduct in-depth interviews with a small number of experts. This ensured they had an in-depth understanding of the process and created space for discussion and feedback on the "intermediate scenarios". Further, involving a larger group of experts with diverse backgrounds in this manner would have been time-consuming and may have resulted in contradicting narratives.

3.3. *Participatory processes*

Participatory processes are a common approach to design socioeconomic and environmental scenarios at the regional and local scale (Kok *et al.* 2014; Nilsson *et al.* 2017; Palazzo *et al.* 2017) as well as to identify local drivers of vulnerability to climate-related hazards (Reckien 2014; Maharjan *et al.* 2017). In this study, the participatory processes were conducted as group discussions during seven community meetings, held in between June and September 2018, across the

neighborhoods of Jamaica Plain and Roxbury (see Figure 2). Local nonprofits, including neighborhood associations, low-income housing organizations, and environmental and civic engagement nonprofits, created space in their regular meetings to allow group discussions (of about 30–45 min) around future socioeconomic development in their neighborhood and drivers of vulnerability to extreme heat. In addition to these group discussions, two longer interviews (of about 2 h) were held with a total of five residents living in low-income housing who expressed interest in sharing their perspectives. Participants were asked to identify: (1) key aspects of socioeconomic and urban development that are important to local communities, (2) neighborhood-level implications of the city-wide socioeconomic scenarios for the identified drivers of local development, and (3) local drivers of vulnerability to extreme heat and their evolution under the local socioeconomic scenarios.

Engaging residents in scenario development is challenging, as participants can have difficulty adapting to the scenario framework (as reported by Nilsson *et al.* 2017). However, these participatory processes are meant to analyze local socioeconomic trends and dynamics and develop scenarios relevant to assess context specific trends in vulnerability. This approach allows to highlight the interaction in between city- and neighborhood-level dynamics, as well as residents' concerns and perspectives regarding future development in their neighborhood. In this case, participants were unfamiliar with scenario development and did not engage when presented with scenario sets, but were interested in talking about current urban and socioeconomic development trends. Moreover, many of the participatory processes took place during or shortly after heat waves, meaning participants were able to recollect and current/recent events and were engaged in the discussion. The participatory processes were thus adapted to engage participants on current urban and socioeconomic development trends and vulnerability to extreme heat. Using this as a baseline, participants were then asked to project future development trends in their neighborhood and the future evolution of drivers of vulnerability to extreme heat, according to assumptions informed by the city-wide scenarios.

Combining residents' perspectives with the city-wide extended SSPs, we created local narratives for our neighborhood-level extended SSPs. These scenarios were therefore built by condensing participants' identified drivers of local socioeconomic development and their evolution under each of the city-wide SSPs. Similarly, participants identified a number of factors driving their vulnerability to extreme heat. We particularly focused this part of the participatory processes on the identification of contextual drivers of vulnerability related to the socioeconomic and urban context (i.e., related to adaptation capacities and the built environment),

rather than personal drivers of vulnerability (i.e., related to individual characteristics, such as age, disability, or health conditions) (a distinction adapted from Kovats and Hajat 2008). These drivers of vulnerability were then summarized and their evolution was predicted under each local scenario.

Altogether, ∼60 residents of the two neighborhoods took part in the participatory processes by voluntarily contributing to group discussions or participating in the longer interviews. Out of the 60 participants, about half (28) identified as being White and either middle- or high-income and for the most part lived in Jamaica Plain. The other half of participants were ethnically diverse (including African–American/Black, Hispanic/Latino, and White residents), in large part low-income, living in affordable housing developments across Jamaica Plan and Roxbury. Most participants were over 40, as relatively few people under 40 attended these community meetings. Although we do not have a detailed demographic profile of our participants, we can note that these proportions roughly match the demographic profiles of these two neighborhoods presented in Section 2, with an over-representation of White residents from Jamaica Plain. This is in part due to two meetings that were conducted in more affluent areas, which had high attendance and participation. Other meetings were held in smaller groups and allowed for longer, more in-depth conversations.

4. Results

4.1. *City-wide scenarios*

4.1.1. Intermediate scenarios resulting from the matching

Results from the scenario matching exercise (Table 1) show that the Stronger Region scenario of the MAPC (MAPC 2014) depicts trends that are comparable to that of SSP1, while the Status Quo scenario can be matched with SSP2. The Stronger Region scenario's main narrative revolves around the economic strength of the city, which attracts a more diverse and young workforce, resulting in high population growth, a trend towards urban living, more compact housing types, and an overall trend towards sustainable urban development. With economic development focused on human well-being, moderately high population growth, and compact and sustainable urban development, SSP1 is indeed a good match to the Stronger Region scenario. The Status Quo scenario's narrative describes an overall perpetuation of historical trends. This consists for instance of moderate population growth and persisting inequalities. In Boston, this scenario describes an ageing population, the continuous decline of household sizes, and overall preferences for single-family homes. With a middle-of-the-road socioeconomic development,

Table 1. Assumptions From the Global SSPs — for SSP1, SSP2, and SSP4 only (O'Neill *et al*. 2017) — and the MAPC Scenarios (MAPC 2014).

	SSP1	SSP2	SSP4	Stronger Region	Status Quo
Economic development	Moderate/high, focus on human well-being	Moderate, uneven	Moderate/low, highly unequal	High	Moderate
Population growth	High	Moderate	Low	High	Moderate
Racial and ethnic diversity	—	—	—	High	Moderate
Favored households arrangement	—	—	—	Multi-family and multi-purpose homes	Single-family homes
Urban development pattern	Concentrated	Historical patterns/ urban Sprawl	Mixed/Dense central areas and urban sprawl	Towards a compact city	Historical patterns/ urban sprawl
Investments in health and education	Increase	Decrease	Unequal	—	—
Inequalities	Decrease (low)	Persist (steady)	Increase (high)	Decrease	Persist

SSP2 is indeed a good match to the Status Quo scenario. SSP4 depicts lower population and economic growth (compared to SSP1 and SSP2), high increase in inequalities, and highly unequal access to public health services. While some of these dynamics and narratives are comparable to the MAPC's Status Quo scenario, they nonetheless show a deviation from current trends. Therefore, SSP4 was not matched to one of the MAPC scenarios.

4.1.2. Main trends of extended scenarios

Experts identified important drivers of urban and socioeconomic development for Boston with regard to the global SSPs and the intermediate scenarios. These drivers are socioeconomic and racial equality, racial/ethnic diversity, housing affordability, institutional coordination and response capacity (particularly in regards to public health), housing affordability, urban development (particularly in regards to access to parks and green spaces), and international immigration (as shown in Table 2). Provided with the intermediate scenarios resulting from the match of SSP1 with *Stronger Region* scenario and of SSP2 with *Status Quo* scenario — and with global SSP4 scenario, which could not be matched with any of the MAPC scenario — experts interpreted and contextualized the main trends for these drivers for the city of Boston. This allowed the construction of three contrasted scenarios at the city-scale (Table 2). SSP1 (Sustainability and Equality) and SSP4 (Increased Inequalities) are presented in comparison to SSP2 (Status Quo).

Table 2. Assumptions of the Extended SSPs for Boston ($SSPs_{Boston}$) for a Few Selected Main Drivers

	$SSP1_{Boston}$	$SSP2_{Boston}$	$SSP4_{Boston}$
Name	Sustainability and Equality	Status Quo	Increased Inequalities
Socioeconomic and racial equality	Increase	Decrease	Strong decrease
Economic growth	Highest	High	Slower growth, characterized by uncertainty
Population growth	Highest	High	Low
Racial/Ethnic Diversity	Highest	High	Low
Housing affordability	Increase	Decrease	Strong decrease
Institutional coordination and response capacity	Highest	Low	Lowest
Access to parks and green spaces	Increase (equitable)	Maintained	Unequitable
International immigration	Increase	Follows historical trends	Decrease

4.1.3. City-wide extended SSPs narratives

In addition to contextualizing the main trends of the intermediate scenarios — and of global SSP4 — for Boston area, the experts' elicitation process proved useful in developing full detailed narratives of each extended SSP for Boston (hereafter SSP_{Boston}).

$SSP1_{Boston}$ — *Sustainability and Equality*: Boston's development and policies focus on reducing poverty and socioeconomic and racial inequalities. Equitable access to infrastructure and services, such as health care, education, and affordable housing, as well as job opportunities are the foundation of this development pathway. This scenario depicts increased international immigration flows and increased federal funds for social and affordable housing programs. High economic growth benefits low- and middle-income households and job growth arises mainly from the education and health care sectors. This prosperity attracts more people to the city, thus resulting in high population growth. Boston's economy benefits from a larger, younger, and more diverse workforce. Urban development focuses on human well-being and equitable access to quality infrastructure and services. Boston follows a trend towards urban living and compact growth as multifamily housing increases. Existing green spaces and street trees are maintained and improved while new spaces are developed and the prevalence of street trees increases throughout the city. At the same time, trust in local government institutions increases, facilitating access to services and care for particularly vulnerable populations. Coordination between local institutions increases, making them more effective and responsive to deal with public health crises and emergencies.

$SSP2_{Boston}$ — *Status Quo*: Boston's development trends remain similar to what has been observed over the past few years. Efforts to address socioeconomic and racial inequality persist, but are overshadowed by national dynamics and the city's overall fast-paced economic development, creating mostly high-wage and low-wage jobs. International immigration follows historical trends. High-end housing is developed throughout the city and the increasing demand for affordable housing is not met by new developments, as funds to develop new affordable housing units lack, resulting in poor housing quality outcomes for low-income people and people of color. Inequalities persist and worsen in some areas. Lower-income residents are increasingly priced out of areas with higher income residents, and segregation increases as low-income and high-income areas become increasingly defined throughout Boston and its neighborhoods. While some improvements and renovations are made to energy and transportation infrastructure as the city grows, overall infrastructure continues to degrade. Existing parks and green spaces are

preserved, but street trees remain more prevalent in higher income areas and few new public green spaces are created. Efforts are made to improve coordination between institutions, although resources lack, offering limited results and making it difficult for them to respond effectively in instances of public health crises and emergencies. Public health officials increase their outreach efforts, particularly for vulnerable population groups, such as undocumented immigrants, people of color, low-income people, and people with limited English proficiency, although trust in government is low.

SSP4$_{\text{Boston}}$ — *Increased Inequalities*: Boston's development trends are highly influenced by a privatization trend that further affects public funding and programs, leading to a sharp decrease in federal funding for social programs and affordable housing as well as more restrictive immigration policies that limit population growth and economic development. The resulting impacts are widespread. Socioeconomic, racial, and income inequalities significantly worsen as the city grows around high-wage industries (finance, education, and health care) and low-wage industries (food preparation and hospitality). The city is increasingly segregated, with high-income and low-income areas. Increasing value of land and high-end developments push for a compact form of growth, although this is not favorable for low-income communities as quality of life, and access to services and infrastructure is increasingly defined by a neighborhood's income level. Housing costs in the city are increasingly high and federal funds lack to develop any new affordable housing units. There is a large gap in between the city's rising poverty rate and existing affordable housing units. Some low-income communities are even pushed out of the city and segregation significantly worsens, restricting access to infrastructure and services to low-income households and people of color. Newly developed green spaces and parks are likely private, and existing green spaces and public areas are not well maintained. The prevalence of chronic diseases increases, disproportionately impacting low-income communities. Investments in health care are uneven, making access to care more difficult for low-income communities and people of color. Public funds lack, affecting coordination in between institutions as well as their individual ability to function.

4.2. *Neighborhood-level scenarios*

Following the participatory processes, the city-wide extended SSPs were further downscaled and contextualized to the two adjacent neighborhoods of Jamaica Plain and Roxbury. Noticeably, most participants — who mainly originated from low-income communities or ethnic minorities — had difficulty imagining more optimistic pathways (such as the one described under SSP1) and were more

convinced that their neighborhood would follow the pathway described in SSP2 or SSP4. Nevertheless, the three city-wide narratives were still extended to the neighborhood scale and led to the development of extended SSPs for the two neighborhoods (hereafter $SSP_{JP\text{-}R}$, standing for "SSPs Jamaica Plain — Roxbury"). These neighborhoods have significantly different demographics (as detailed in Section 2), although they both have higher income and lower income pockets and are geographically close. Their dynamics are analyzed as a whole — with a focus on perspectives coming from lower-income residents and higher-income residents from both neighborhoods. However, some contrasts are offered for each neighborhood.

$SSP1_{JP\text{-}R}$ — ***Sustainability and Equality*:** Socioeconomic and racial inequalities are significantly reduced in these neighborhoods, due to widespread policy and urban development efforts to reduce poverty and ensure equity in access to quality housing, infrastructure, and services. Trust in government increases, as assistance is made accessible for lower-income families, people of color, and immigrants. As population growth in the city increases, neighborhoods densify, but affordable and quality housing is ensured for lower-income families. Old industrial areas and abandoned buildings are re-purposed to allow both compact and efficient growth and an increase in the prevalence of green spaces and vegetation across the neighborhoods. Access to public transportation increases, as buses and trains run more frequently, and large investments in infrastructure render them more reliable and comfortable. This allows a more widespread use of public transportation and reduces congestion.

$SSP2_{JP\text{-}R}$ — ***Status Quo*:** Socioeconomic and racial inequalities keep increasing in these neighborhoods. Existing affordable housing units remain, but real estate costs keep on rising as the neighborhoods' population becomes increasingly white and high-income. Low-income people are priced-out of their neighborhood, while homeless people have to move to other areas. However, low-income pockets remain, especially in Roxbury, along with subsidized housing units. Low-income communities, immigrant communities, and communities of color still struggle to get access to affordable, quality housing and to welfare programs, further increasing inequalities. Trust in government from these communities remains low. New apartment buildings are built on old industrial sites and lack vegetation. Although existing green spaces are maintained, there is an overall decrease in the presence of street trees and vegetated areas in these neighborhoods. Although some investments are made in public transportation, they are not sufficient to keep up with degrading infrastructure, thus further affecting reliability and efficiency for passengers, as well as overall comfort.

SSP4$_{\text{JP-R}}$ — ***Increased Inequalities*:** Socioeconomic and racial inequalities rise rapidly due to high-wage and low-wage job growth and a lack of effort by local and federal government to fight them. Access to affordable housing and assistance programs for low-income people and people of color is increasingly difficult and restricted, while trust in government is extremely low. The impacts of these trends are magnified in comparison to the Status Quo scenario. These neighborhoods become increasingly gentrified and segregated, displacing many low-income and homeless people. Few low-income pockets remain, mainly in Roxbury, where quality of life and access to services is compromised. This pathway favors a compact form of growth, with new high-end developments throughout the neighborhood. New green spaces are privatized and the overall prevalence of trees decreases, as new high-income apartment buildings leave little room for vegetation and trees are cut down so they will not fall on new buildings. Higher-income residents increasingly use individual motorized transportation and ride-sharing services, increasing congestion. Public transportation infrastructure degrades, further compromising accessibility and reliability. This particularly affects low-income residents and those with health conditions and physical disabilities who rely on public transportation.

4.3. *Future vulnerability*

4.3.1. Local drivers of vulnerability

The participatory processes were not only useful to design the neighborhood-level extended SSPs, but also used to identify the local drivers of vulnerability to extreme heat. Six key drivers of local vulnerability were identified, namely (1) socioeconomic and racial inequalities, (2) access to air conditioning (AC), (3) social isolation, (4) access to transportation, (5) the prevalence of green spaces and trees, and (6) infrastructure and the built environment. These identified local drivers of vulnerability to extreme heat are similar to those identified in existing literature (e.g., Coutts *et al.* 2015; Curriero *et al.* 2002; Harlan *et al.* 2006; O'Neill *et al.* 2005; Reid *et al.* 2009; Wilhelmi and Hayden 2010). However, the participatory methods employed provide locally-informed, detailed narratives which allow to highlight aspects of socioeconomic development and vulnerability that are considered important by local residents.

(1) **Inequalities** — Low-income residents and residents of color identified socioeconomic and racial inequalities as being a core aspect of their vulnerability, as they exacerbate the effects of other drivers, such as their ability to afford air conditioning and quality housing as well as their access to green spaces and trees, transportation, and quality health care.

(2) **Access to AC** — A large proportion of residents rely on window AC units, as many older buildings and homes do not have central AC. In higher-income areas, residents reported to have at least a few units for their homes, but often chose to stay in just one or two rooms, thus significantly affecting their daily routine. While most people have access to AC in higher income areas, many residents in lower-income areas reported not being able to afford AC units and/or the high utility bills related to their use. In some housing developments, residents had access to an air conditioned community room during periods of extreme heat, although they reported it was often not used by residents as there was nothing for them to do there. Residents, both in higher- and lower-income areas, were concerned about the lack of AC in public schools — concerned both for the children's health and their ability to learn during extreme heat events (Figure 4(a)).

(3) **Social isolation** — Residents generally reported that extreme heat affected their desire to go outside and engage in their usual social activities (Figure 4(b)).

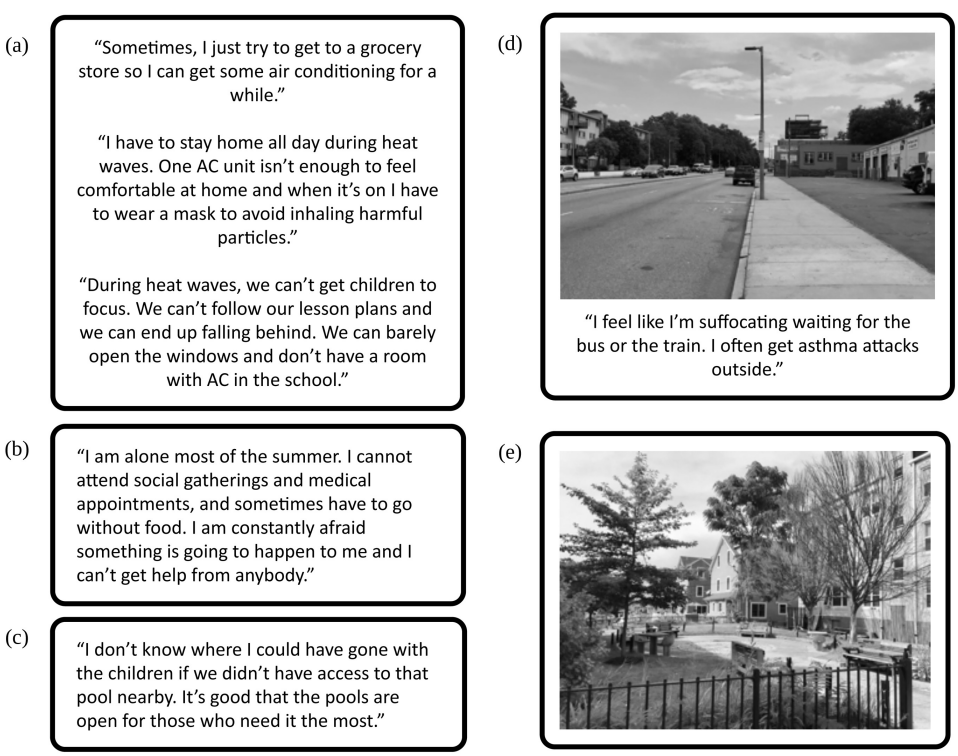

Fig. 4. Selection of Quotes (a, b, c, d) from Residents Involved in the Participatory Processes and Pictures (d, e) to Emphasize Certain Drivers of Heat-related Vulnerability Raised by the Residents

Residents in higher-income areas reported everyone remained indoors during periods of extreme heat, as they generally had access to AC. In lower-income areas, although residents without AC (or with too few units) had a tendency to go outdoors, residents who were particularly sensitive to the heat, such as elderly people and people with health conditions, tended to remain indoors. Participants were overall concerned of social isolation, particularly among the elderly and people with health conditions, as they were forced to stay indoors. Residents were concerned extreme heat further isolated the elderly and people especially sensitive to the heat, and rendered them unable to go to work, to the pharmacy, to medical appointments, to get groceries, or attend social gatherings. Participants particularly sensitive to the heat reported it affected their ability to get assistance when they needed it.

(4) **Access to transportation** — During periods of extreme heat, most residents reported they avoid moving around as they felt the use of public transportation resulted in high exposure to the heat. Although many buses and trains are air conditioned, it is not always very effective (for instance during rush hour) and transit stops are particularly hot. Underground train stops are expected to be hot and uncomfortable, and numerous bus stops do not have sufficient shade nearby (Figure 4(d)). Many residents also reported the use of AC in buses and trains often renders it too cold, causing them to be exposed to large temperature differences, particularly when required to change buses or trains. For these reasons, many avoided using public transportation as much as possible. Residents in higher-income areas reported that during periods of extreme heat, they were much more likely to use ride-sharing services rather than use public transportation, walk, or bike.

(5) **Prevalence of green spaces and trees** — Residents perceived there is an overall lack of vegetation, green spaces, and trees in their neighborhoods. While existing parks are maintained, residents noticed there has been a decrease in the overall prevalence of trees and vegetation in their streets, as old trees are cut down and new developments often lack any kind of vegetation. Residents recognized the importance of having trees and green spaces in their neighborhoods as they provide a significant source of cooling. Participants considered the prevalence of street trees as particularly important when trying to get around, as trees can provide shade in the street to people who are walking, getting to transit stops, or waiting for the bus. Residents in lower-income areas noticed that the prevalence of trees and green spaces is much scarcer in their neighborhood (Figure 4(e)) than in higher-income areas. However, in lower-income areas, participants reported more people spent time outside during periods of extreme heat, mostly in streets, parks, and in

the free water parks and pools made available by the city (Figure 4(c)). Some residents in lower-income areas expressed their desire to have more green spaces to be able to stay outside in the heat and have social gatherings in the summer.

(6) **Infrastructure and built environment** — Residents were generally concerned with ageing infrastructure, specifically the electric grid and transportation infrastructure, which have been subject to failure during extreme weather events (including extreme heat) in the region. Increasing population density, combined with an ageing infrastructure, increased their concerns about power outages, which would compromise access to AC, fridges, fans, and other necessary devices. Residents were concerned about how this would affect already vulnerable populations, for instance the elderly or non-English speakers, who may not have access to information related to power outages, maintenance, and assistance. Participants also witnessed the use of AC causing several power outages in older buildings in their neighborhood, resulting in several hours without access to power during extreme heat events.

4.3.2. Future vulnerability assessment

The identification of local drivers of vulnerability — through participatory processes — and their combination with neighborhood-level socioeconomic scenarios (that is, the extended SSPs) allows to determine the influence of different socioeconomic pathways for future vulnerability to extreme heat and challenges to adaptation at the neighborhood-scale. Challenges to adaptation are defined as environmental and socioeconomic conditions that make adaptation more difficult and therefore increase future climate risks (O'Neill *et al.* 2014). Our locally extended SSPs detail challenges to adaptation (rather than mitigation), which allows a vulnerability assessment focused on vulnerability arising from socioeconomic and urban conditions (or "contextual" vulnerability). Detailed trends for key drivers of vulnerability under each extended SSP — and the resulting potential impacts on society — are presented in Table 3. Figure 5 summarizes relative levels of challenges to adaptation for each driver of vulnerability according to the narratives presented in Table 3. Overall, $SSP1_{JP\text{-}R}$, being a sustainable development and social equality pathway, depicts a neighborhood where challenges to adaptation to extreme heat are low, due to efforts made at all levels to reduce inequalities and poverty as well as to promote sustainable urban development and investments in critical infrastructure. In contrast, $SSP4_{JP\text{-}R}$ depicts a neighborhood with high challenges to adaptation to extreme heat for the increasing number of low-income people, who often ends up in poor quality housing. This results in uncertain access

Table 3. Trends of Key Drivers of Local Vulnerability to Heat under each Neighborhood-level Extended SSPs as well as the Resulting Potential Extreme Temperature Impacts on the Society

	$SSP1_{JP\text{-}R}$	$SSP2_{JP\text{-}R}$	$SSP4_{JP\text{-}R}$
Socioeconomic and racial inequalities	Inequalities decrease, resulting in a lower poverty rate and decreased segregation. Trust in government institutions increases and facilitates access to assistance programs for low-income people and people of color, while affordable and quality housing increases throughout the neighborhood.	Keep increasing. Low-income people and people of color continue to struggle for access to quality housing. The neighborhood's population becomes increasingly white and high-income. Low-income residents are progressively priced-out of their neighborhood.	Rising inequalities feed into economic instability for low-income residents. The rising poverty rate and lack of new affordable housing units further segregate neighborhoods, which becomes essentially high-income and white with pockets of low-income communities.
Access to AC	Lower-income people have increased access to AC as inequalities decrease and access to assistance programs increases. In older buildings, residents still have to rely on window units, but special attention is paid to people especially sensitive to the heat. With increased public funding available, cooling is offered in public schools.	As local efforts increasingly seek to reach out to vulnerable population groups, people determined as especially vulnerable are able to get access to basic cooling features. New buildings developments have central AC, and there is an increasing prevalence of AC in public schools.	Increasing inequalities restrict access to AC for low-income people, who cannot afford AC units or the increased utility bills related to their use. On the other hand, higher-income people do not struggle for access to AC and all new high-end developments have central AC.

Table 3. (*Continued*)

	$SSP1_{JP\text{-}R}$	$SSP2_{JP\text{-}R}$	$SSP4_{JP\text{-}R}$
Social isolation	Social isolation remains an issue in the neighborhood, but its effect on vulnerability to extreme heat is mitigated by increased prevalence of AC, increased access to transportation, and efficient institutions aiming to reach vulnerable populations.	The awareness of especially vulnerable people and increased coordination across institutions has the potential to help some people, but the lack of funds and resources prevents further progress. The results of new programs to reduce social isolation are limited and inequalities deeply affect the ability of socially isolated people to cope with extreme heat.	Worsening public transportation infrastructure, increasing inequalities, lack of access to assistance programs, and lack of trust in government increase the burden of social isolation regarding vulnerability to extreme heat, as it is more difficult for socially isolated people to get access to the assistance and care they need during periods of extreme heat.
Access to transportation	Investments in public transportation infrastructure increase access to comfortable and reliable public transportation. While only small improvements at transit stops make them more comfortable, increased frequency and reliability make public transportation more efficient and desirable, increasing the ability of people who are especially sensitive to the heat to get around.	Continuing investment in public transportation infrastructure is insufficient to keep it from degrading, resulting in increasingly unreliable and inefficient service for passengers. People who are dependent on public transportation and sensitive to heat are further isolated, as no actions are taken to cool down transportation infrastructure such as bus stops.	Public transportation infrastructure keeps degrading. As segregation increases, restricting access to infrastructure to low-income people and people of color, the public transportation system becomes unreliable and inefficient. This makes it difficult for people who depend on public transportation to tend to their needs during periods of extreme heat.

Table 3. (*Continued*)

	$SSP1_{JP\text{-}R}$	$SSP2_{JP\text{-}R}$	$SSP4_{JP\text{-}R}$
Prevalence of green spaces and trees	Prevalence of green spaces and trees increases evenly across the neighborhood, thus serving cooling and recreational purposes. The increase in trees makes it more comfortable for residents to walk in the streets, and get to transit stops, stores, etc. Moreover, increased access to green spaces favors outdoor activities and gatherings.	Prevalence of green spaces and trees is generally maintained across the neighborhood. Although some local efforts to plant trees are successful, some trees are cut down. However, green spaces and trees still lack in lower-income areas, where streets still lack shade and vegetation.	Existing parks and vegetation in low-income areas are not well maintained. In higher-income areas, new green spaces are prevalent but likely private, making it even more difficult for low-income people who do not have AC to find cooling features outdoors.
Infrastructure and the built environment	While new buildings have central AC, old buildings and infrastructure are maintained and renovated to accommodate efficient and reliable cooling. Investments are made in public infrastructure, ensuring their resilience to climate-related hazards and access to energy and cooling features during periods of extreme heat.	Although some minor investments are made in infrastructure, it continues to degrade, further compromising access to basic infrastructure and services (such as energy and cooling features) during extreme heat, as it increases risks of failures.	Public infrastructure degrades quickly, as investments lack. Due to the privatization trend, infrastructure in low-income neighborhoods is degrading and unreliable, particularly during heat waves, while higher-income areas have more reliable access.
Extreme temperature impacts on the society	Globally low, mainly due to an increased access to cheap AC, an increased in the prevalence of green areas, and social policies leading to lower inequalities.	Globally medium to high, mainly due to high inequalities and unreliable transportation systems, but mitigated to some extent by an increased access to AC.	Globally high, mainly due to the high inequalities, lack of green spaces, lack of access to transportation and social isolation of the elderly.

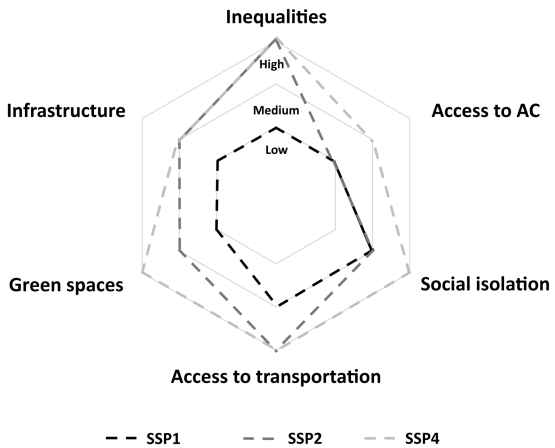

Figure 5. Challenges to Adaptation (Low, Medium, or High) under the Three Neighborhood-level Extended SSPs, for Each Drivers of Vulnerability to Extreme Heat

to AC and low access to reliable and comfortable transportation. On the other hand, the increasingly white and high-income population in the neighborhood has sufficient access to resources to cope efficiently with extreme heat. Finally, $SSP2_{JP\text{-}R}$, being a middle-of-the-road pathway, depicts medium to high challenges to adaptation, in large part due to increasing socioeconomic and racial inequalities, restraining access to sufficient resources for low-income people to cope with and adapt to extreme heat, as well as to a lack of sufficient investments in critical and transport infrastructure.

5. Discussion and conclusion

In this study, we applied a three-step approach — made of scenario matching, experts' elicitation, and participatory processes — to extend the global SSPs to the City of Boston and two adjacent neighborhoods. Both the city-wide and neighborhood-level extended SSPs are consistent with the global SSPs, while being contextualized and relevant at the local scale. Taking advantage of the participatory processes used to develop the neighborhood-level scenarios, we also identified key local drivers of vulnerability to extreme heat and qualitatively assessed future heat vulnerability in the neighborhoods of Jamaica Plain and Roxbury under the three contrasted extended SSPs. Overall, $SSP1_{JP\text{-}R}$, narrates low challenges to adaptation to extreme heat, due to efforts made to reduce inequalities and to promote sustainable urban development in these neighborhoods. On the other hand, $SSP4_{JP\text{-}R}$ depicts high challenges to adaptation to extreme heat for the

increasingly low-income population, while higher income residents have access to more resources to cope with extreme heat. $SSP2_{JP\text{-}R}$, a middle-of-the-road pathway, depicts medium to high challenges to adaptation, in large part due to increasing socioeconomic and racial inequalities. Such an application of the extended SSPs sheds light on their usefulness at the local scale to inform vulnerability assessments, as it allows to highlight locally-determined drivers of vulnerability to extreme heat and their evolution under contrasted socioeconomic development trends. Given the contextual nature of vulnerability, taking local socioeconomic development trends into account allow a locally informed analysis of future trends in vulnerability. Further, at a local level, the combination of climatic and socioeconomic scenarios, representing a range of possible futures, intends to inform "no regret" policies and highlight adaptation and mitigation options (as described by Van Vuuren *et al.* 2014).

Nevertheless, this research is associated with a number of caveats. First, matching the global SSPs with local scenarios — as a basis of their extension — requires the existence of scenario sets at the city-scale, which may be challenging. In the case of the City of Boston, we were able to retrieve only two different city-wide scenarios (MAPC 2014), which highly restricted the matching with the global SSPs. While the number of socioeconomic and environmental scenarios is increasing (Hunt *et al.* 2012; Aerts *et al.* 2013), most of them are global or regional and not city-specific. Second, the scenario matching that we performed was purely qualitative and did not rely on structured methods such as pairwise comparisons (Rohat *et al.* 2018) or cross-impact balances (Schweizer and Kurniawan 2016). Third, we were not able to quantify the extended SSPs. While the expert's elicitation allowed to develop detailed narratives of the city-wide SSPs, experts had difficulty providing quantified estimations simply based on narratives, demonstrating the difficulty of quantifying scenarios using participatory approaches (Birkmann *et al.* 2013). Moreover, as we focused on a relatively small group of experts (as detailed in Section 3.2), approaches to quantify experts' views — e.g., the fuzzy set theory (Rohat 2018) — were not applicable. Fourth, it proved difficult to engage residents in discussing future trends, as the overwhelming majority of residents involved in the participatory processes were uninterested in and unfamiliar with the scenario building process and were much more interested in current issues. Similar difficulties are often reported in scenario building studies, including studies extending the SSPs (Nilsson *et al.* 2017). Based on these difficulties, participatory processes were adapted to engage participants on issues more relevant and interesting to their community (as described in Section 3.3). With these adaptations, participants appeared generally engaged and willing to share their perspective. However, this limited our ability to gather

feedback from participants on the neighborhood-level extended SSPs and vulnerability assessment.

Overall, while we — and the experts — faced challenges in applying the global SSPs' narratives at the city-scale, we found the global SSPs to provide internally consistent sets of boundary conditions, which guide the development of local narratives and allow the articulation of global and local dynamics when building scenarios. Framing local scenario development within the SSP framework also allows for cross-case study comparison of the influence of socioeconomic pathways on future climate-related adaptation and mitigation challenges, rendering local research more accessible and relevant to research across sectors or scales. While there are currently only a few extended SSPs at the city scale, we believe that the easy-to-implement extension approach that we presented in this research could be taken on board by the IAV community to develop extended SSPs in other cities, thus allowing for cross-case studies comparison in the near future. Framing local scenarios within the SSP framework also enables their subsequent combination with climate change scenarios (RCPs) to explore future climate risks under socioeconomic and climatic uncertainty (Rohat *et al.* 2019a). For example, if our local SSPs were to be combined with downscaled RCPs (such as intended by the scenario matrix architecture, described by Van Vuuren *et al.* 2014), this would provide a wide range of possible socioeconomic and climatic futures having different implications for heat stress risk in our Boston neighborhoods. The increasing quantification of the global SSPs at the sub-national scale, e.g., Hauer (2019), opens the door to urban scale assessments of future climate risks based on the SSP*RCP framework. Such assessments would ultimately provide local stakeholders, such as policy makers and decision makers within local governments, with better estimates of future climate risks and a better understanding of the ways in which both socioeconomic development and climate change shape future climate risks in urban areas.

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References

Absar, SM and Preston BL (2015). Extending the shared socioeconomic pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environmental Change*, 33: 83–96.

Aerts, JC, Feyen L, Hochrainer-Stigler S, Brenden J, Hudson P and Veldkamp TIE (2013). Inventory of Existing Risk Scenarios, ENHANCE EU Project.

Birkmann, J, Cutter SL, Rothman DS, Torsten W, Garschgen M, van Ruijven, B, O'Neill, B, Preston BL, Kienberger S, Cardona OD, Siagian T, Hidayati D, Setiadi N, Binder CR, Hughes B and Pulwarty R (2013). Scenarios for vulnerability: Opportunities and constraints in the context of climate change and disaster risk. *Climatic Change*, 1: 53–68.

BPDA (2017). Boston's Economy Report, Boston Planning and Development Agency Research Division.

BPDA (2018). Boston in Context: Neighborhoods. Boston Planning and Development Agency Research Division.

BPDA (2019). Approaches to Immigration Policy and their Impacts on Boston. Boston Planning and Development Agency Research Division.

BRC (2016). *Boston's Preliminary Resilience Assessment. The Bezqginning of a Shared Journey to Healing, Connections, and Action*, Mayor's Office of Resilience, Boston Resilience Collaborative group.

Busch, G (2006). Future European agricultural landscapes — What can we learn from existing quantitative land use scenario studies?*Agriculture, Ecosystems & Environment*, 114: 121–140.

City of Boston (2016). *Vulnerability assessment*, Climate Ready Boston, available at: https://www.boston.gov/departments/environment/climate-ready-boston.

Cooley, H, Moore E, Heberger M and Allen L (2012). Social Vulnerability to Climate Change in California. Pacific Institute.

Coutts, E, Ito K, Nardi C and Vuong T (2015). Planning Urban Heat Island Mitigation in Boston. The Trust for Public Land.

Crespo Cuaresma, J (2017). Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, 42: 226–236.

Curriero, FC, Heiner KS, Samet JM, Zeger SL, Strug L and Patz JA (2002). Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, 155: 80–87.

de Sherbinin, A and Bardy G (2016). Social vulnerability to floods in two coastal megacities: New York City and Mumbai. *Vienna Yearbook of Population Research*, 1: 131–165.

de Sherbinin, A, Bukvic A, Rohat G, Gall M, McCusker B, Preston B, Apotsos A, Fish C, Kienberger S, Muhonda P, Wilhelmi O, Macharia D, Shubert W, Sliuzas R, Tomaszewski B and Zhang S (2019). Climate vulnerability mapping: A systematic review and future prospects, *Wiley Interdisciplinary Reviews: Climate Change*, https://doi.org/10.1002/wcc.600.

Douglas, E, Kirshen P, Hannigan R, Herst R and Palardy A (2016). Climate Cange and Sea Level Rise Projections for Boston, Boston Research Advisory Group.

Ebi, KL (2013). Health in the new scenarios for climate change research. *International Journal of Environmental Research and Public Health*, 11: 30–46.

Ebi, KL, Hess JJ and Isaksen TB (2016). Using uncertain climate and development information in health adaptation planning. *Current Environmental Health Reports*, 3: 99–105.

Frame, B, Lawrence J, Ausseil A, Reisinger A and Daigneault A (2018). Adapting global shared socioeconomic pathways for national and local scenarios. *Climate Risk Management*, 21: 39–51.

Garschagen, M and Romero-Lankao P (2013). Exploring the relationships between urbanization trends and climate change vulnerability. *Climatic Change*, 133: 37–52.

Guerreiro, SB, Dawson RJ, Kilsby C, Lewis E and Ford A (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, 13(3), https://doi.org/10.1088/1748-9326/aaaad3.

Harlan, SL, Brazel AJ, Prashad L, Stefanov WL and Larsen L (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science & Medicine*, 63(11): 2847–2863.

Hasegawa, T, Fujimori S, Takahashi K and Masui T (2015). Scenarios for the risk of hunger in the twenty first century using Shared Socioeconomic Pathways. *Environmental Research Letters*, 10(1), doi: 10.1088/1748-9326/10/1/014010.

Hauer, ME (2019). Population projections for U.S. counties by age, sex, and race controlled to shared socioeconomic pathway. *Scientific Data*, 6, https://doi.org/10.1038/sdata.2019.5.

Hunt, DVL, Lombardi DR, Atkinson S, Barber ARG, Barnes M, Boyko CT, Brown J, Bryson J, Butler D, Caputo S, Caserio M, Coles R, Cooper RFD, Farmani R, Gaterell M, Hale J, Hales C, Hewitt CN, Jankovic L, Jefferson I, Leach J, MacKenzie AR, Memon FA, Sadler JP, Weingaertner C, Whyatt JD and Rogers CDF (2012). Scenario archetypes: Converging rather than diverging themes. *Sustainability*, 4: 740–772.

Jiang, L and O'Neill BC (2017). Global urbanization projections for the shared socioeconomic pathways. *Global Environmental Change*, 42; 193–199.

Jones, B and O'Neill BC (2016). Spatially explicit global population scenarios consistent with the shared socioeconomic pathways. *Environmental Research Letters*, 11(8), doi: 10.1088/1748- 9326/11/8/084003.

Kamei, M, Hanaki K and Kurisu K (2016). Tokyo's long-term socioeconomic pathways: Towards a sustainable future. *Sustainable Cities and Society*, 27: 73–82.

Kashem, SB, Wilson B and Van Zandt S (2016). Planning for climate adaptation: Evaluating the changing patterns of social vulnerability and adaptation challenges in three coastal cities. *Journal of Planning Education and Research*, 36: 304–318.

Kemp-Benedict, E, de Jong W and Pacheco P (2014). Forest futures: Linking global paths to local conditions. *IUFRO World Series*, 32: 539–553.

Knol, AB, Slottje P, van der Sluijs JP and Lebret E (2010). The use of expert elicitation in environmental health impact assessment: A seven step procedure. *Environmental Health*, 9(19), doi: 10.1186/1476-069X-9-19.

Kok, K, Gramberger, M, Zellmer, K, Simon, KH, Jager J and Omann I (2013). Report on the new methodology for scenario analysis and based on an analysis of past scenario exercises. CLIMSAVE EU Project.

Kok, K, Bärlund, I, Flörke, M, Holman I, Gramberger M, Sendzimir J, Stuch B and Zellmer K (2014). European participatory scenario development: Strengthening the link between stories and models. *Climatic Change*, 128: 187–200.

Kok, K, Pedde S, Gramberger M, Harrison PA and Holman I (2019). New European socio-economic scenarios for climate change research: Operationalising concepts to extended the shared socioeconomic pathways. *Regional Environmental Change*, 19: 643–654.

Kovats, RS and Hajat S (2008). Heat stress and public health: A critical review. *Annual Review of Public Health*, 29: 41–55.

Kriegler, E, O'Neill, BC, Hallegatte S, Kram T, Lempert RJ, Moss RH and Wilbanks T (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, 22: 807–822.

Li, X, Zhou Y, Eom J, Yu S and Asrar GR (2019). Projecting global urban area growth through 2100 based on historical time-series data and future shared socioeconomic pathways. *Earth's Future*, 7: 351–362.

MAPC (2014). Population and Housing Demand Projections for Metro Boston. Boston, USA: Metropolitan Area Planning Council.

Maharjan, SK, Maharjan KL, Tiwari U and Sen NP (2017). Participatory vulnerability assessment of climate vulnerabilities and impacts in Madi Valley of Chitwan district, Nepal. *Cogent Food & Agriculture*, 3(1), http://dx.doi.org/10.1080/23311932.2017.1310078.

Maury, O, Campling L, Arrizabalaga H, Aumont O, Bopp L, Merino G, Squires D, Cheung W, Goujon M, Guivarch C, Lefort S, Marsac F, Monteagudo P, Murtugudde R, Österblom, H, Pulvenis JF, Ye Y and van Ruijven BJ (2017). From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): Building policy-relevant scenarios for global oceanic ecosystems and fisheries. *Global Environmental Change*, 45: 203–216.

Melaas, EK, Wang JA, Miller DL and Friedl MA (2016). Interactions between urban vegetation and surface urban heat islands: A case study in the Boston metropolitan region. *Environmental Research Letters*, 11(5), doi: 10.1088/1748-9326/11/5/054020.

Nilsson, AE, Bay-Larsen, I, Carlsen H, van Oort, B, Bjørkan, M, Jylhä K, Klyuchnikova E, Masloboev V and van der Watt L-M (2017). Towards extended shared socioeconomic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. *Global Environmental Change*, 45: 124–132.

O'Neill, MS, Zanobetti A and Schwartz J (2005). Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *Journal of Urban Health*, 82(2): 191–197.

O'Neill, BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R and Van Vuuren DP (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122: 387–400.

O'Neill, BC, Kriegler E, Ebi KL, Kemp-Benedict, E, Riahi K, Rothman DS, van Ruijven, BJ, Van Vuuren, DP, Birkmann J, Kok K, Levy M and Solecki W (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42: 169–180.

Palazzo, A, Vervoort JM, Mason-D'Croz, D, Rutting L, Havlík, P, Islam S, Bayala J, Valin H, Kadi Kadi, HA, Thornton P and Zougmore R (2017). Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, 45: 227–242.

Reckien, D (2014). Weather extremes and street life in India — Implications of fuzzy cognitive mapping as a new tool for semi-quantitative impact assessment and ranking of adaptation measures. *Global Environmental Change*, 26: 1–13.

Reid, CE, O'neill, MS, Gronlund CJ, Brines SJ, Brown DG, Diez-Roux AV and Schwartz J (2009). Mapping community determinants of heat vulnerability. *Environmental Health Perspectives*, 117(11): 1730–1736.

Reimann, L, Merkens J-L and Vafeidis AT (2018). Regionalized shared socioeconomic pathways: Narratives and spatial population projections for the Mediterranean coastal zone. *Regional Environmental Change*, 18: 235–245.

Revi, A, Satterthwaite, DE, Aragon-Durand, F, Corfee-Morlot, J, Kiunsi RBR, Pelling, M, Roberts D and Solecki W (2014). Urban Areas. In: Climate Change 2014: Impacts, Adaptation and Vulnerability. Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Rohat, G, Flacke J, Dao H and van Maarseveen M (2018). Co-use of existing scenario sets to extend and quantify the shared socioeconomic pathways. *Climatic Change*, 151 (3–4): 619–636.

Rohat, G, Flacke J, Dosio A, Pedde S, Dao H and van Maarseveen M (2019a). Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, 172: 45–59.

Rohat, G, Wilhelmi O, Flacke J, Monaghan A, Gao J, Dao H and Van Maarseveen M. (2019b) Characterizing the role of socioeconomic pathways in shaping future urban heat-related challenges. *Science of the Total Environment*, 695: 133941.

Rohat, G (2018). Projecting drivers of human vulnerability under the shared socioeconomic pathways. *International Journal of Environmental Research and Public Health*, 15(3), doi: 10.3390/ijerph15030554.

Romero Lankao, P and Qin H (2011). Conceptualizing urban vulnerability to global climate and environmental change. *Current Opinion in Environmental Sustainability*, 3(3): 142–149.

Samir, KC and Lutz W (2014). Demographic scenarios by age, sex and education corresponding to the SSP narratives. *Population and Environment*, 35: 243–260.

Schweizer, VJ and Kurniawan JH (2016). Systematically linking qualitative elements of scenarios across levels, scales, and sectors. *Environmental Modelling & Software*, 79: 322–333.

Sellers, S and Ebi KL (2017). Climate change and health under the shared socioeconomic pathway framework. *International Journal of Environmental Research and Public Health*, 15(1), doi: 10.3390/ijerph15010003.

Street, M, Reinhart C, Norford L and Ochsendorf J (2013). Urban heat island in Boston — An evaluation of urbain air temperature models for predicting building energy use. *Proceedings of Building Simulations*. Chambery: France.

U.S. Census Bureau (2018). ACS 1-Year Estimate Subject Tables.

Van Ruijven, BJ, Levy MA, Agrawal A, Biermann F, Birkmann J, Carter TR, Ebi KL, Garschagen M, Jones B, Jones R, Kemp-Benedict, E, Kok M, Kok K, Lemos MC, Lucas PL, Orlove B, Pachauri S, Parris TM, Patwardhan A, Petersen A, Preston BL, Ribot J, Rothman DS and Schweizer VJ (2014). Enhancing the relevance of shared socioeconomic pathways for climate change impacts, adaptation and vulnerability research. *Climatic Change*, 122(3): 481–494.

Van Vuuren, DP and Carter TR (2013). Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old. *Climatic Change*, 122(3): 415–429.

Van Vuuren, DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith SJ and Rose SK (2011). The representative concentration pathways: An overview. *Climatic Change*, 109: 5–31.

Van Vuuren, DP, Kriegler E, O'Neill, BC, Ebi KL, Riahi K, Carter TR, Edmonds J, Hallegate S, Kram T, Mathur R and Winkler H (2014). A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change*, 122(3): 373–386.

Wada, Y, Flörke, M, Hanasaki N, Eisner S, Fischer G, Tramberend S, Satoh Y, van Vliet MTH, Yillia P, Ringler C, Burek P and Wiberg D (2016). Modeling global water use for the 21st century: The water futures and solutions (WFaS) initiative and its approaches. *Geoscientific Model Development*, 9: 175–222.

Wilhelmi, OV and Hayden MH (2010). Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. *Environmental Research Letters*, 5(1), doi: 10.1088/1748-9326/5/1/014021.

Yao, M, Tramberend S, Kabat P, Hutjes RWA and Werners SE (2017). Building regional water-use scenarios consistent with global shared socioeconomic pathways. *Environmental Processes*, 4(1): 15–31.

Zandersen, M, Hyytiäinen, K, Meier HEM, Tomczak MT, Bauer B, Haapasaari PE, Olesen JE, Gustafsson BG, Refsgaard JC, Fridell E, Pihlainen S, Le Tissier MDA, Kosenius A-K and Van Vuuren DP (2019). Shared socio-economic pathways extended for the Baltic Sea: Exploring long-term environmental problems. *Regional Environmental Change*, 19(4): 1073–1086.