Supporting Urban Adaptation to Climate Change: What Role Can Resilience Measurement Tools Play?

Sara Mehryar[1,3], Idan Sasson[2], Swenja Surminski[1]

1. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK
2. Climate Policy Initiative, London, UK
3. Corresponding author: s.mehryar@lse.ac.uk - 32 Lincoln's Inn Fields, London WC2A 3PH

Summary: Cities are emerging as leading forces for climate change adaptation and resilience. Many approaches and tools have been developed and used to measure climate resilience in cities. In this study, we explore if and how such tools can be or have been used to support *decision-making* for building urban climate resilience. We applied a deep analysis of 27 tools developed for measuring urban climate resilience and supplemented it with semi-structured interviews with experts who implemented such tools in over 100 cities around the world. Our analysis shows that only about one-third of these tools are designed to support implementing resilience actions while the rest mainly focus on sharing knowledge and raising awareness. We also observed a prevailing focus on evaluating coping and incremental adaptation capacities (as opposed to transformative capacities) against climate risks in such tools, which tends to trigger short-term fix rather than long-term solutions. Therefore, we argue that urban climate resilience measurement tools need to 1) support action implementation processes as much as assessing outcomes, and 2) consider the enabling environment for enhancing transformative capacities as much as coping and incremental adaptation capacities of cities. Finally, we explore challenges and opportunities of implementing resilience actions drawn from end-users' insights.

Keywords: urban climate resilience, resilience measurement, decision-making, urban governance, decision support tools

1. Introduction

Urban areas serve as centres of economic activity, technology, and innovation, and are crucial in supporting the broader response to climate risks (Hughes and Sarzynski, 2015; Singh et al., 2021; Rosenzweig et al., 2010; Mi et al., 2019). However, the process of urbanization and dynamics of cities can have a profound impact on increasing climate change. For instance, urban areas are major sources of anthropogenic carbon dioxide emissions from the burning of fossil fuels for heating/cooling, industrial processes, and transportation of people and goods (Grimmond, 2007). Clearing land for cities and changing the vegetative land cover associated with the construction and functioning of cities also increase the heat capacity of the urban areas. The so-called urban heat island is one of the main drivers or exacerbator of global warming and climate change (Argüeso et al., 2014). In addition, rapid urbanization and urban sprawl expose more people to a wide array of climate risks including sea-level rise, heat waves, various types of flooding, windstorms, and landslides. Hanson et al. (2011) estimate that by the 2070s, total population of the port cities exposed to coastal flood events could grow more than threefold, and a recent study by Wolff et al. (2020) estimate that by 2100 the total urban exposure of 10 European countries to coastal flood risks could increase up to 104% due to the combined effects of sea-level rise, population growth, and urbanization. These pose real dangers to urban residents, their livelihoods, and assets, as well as businesses operating in the cities and critical infrastructure serving them. The socio-economic vulnerabilities caused by rapid urbanization and economic transformation can also increase the sensitivity and weaken the coping and adaptive capacities of communities in response to climate risks (Garschagen and Romero-Lankao, 2015).

As cities continue to struggle with the uncertainties and challenges of climate change, "urban climate resilience" has received traction as a holistic framework for managing risk and planning effective solutions by urban planners and policy-makers in cities (Marschütz et al., 2020; Bellinson and Chu, 2019; Meerow et al., 2016; Leichenko, 2011). In this paper we define 'climate resilience'[1] as capacity of people and systems to sustain and improve their livelihood and development opportunities and wellbeing despite environmental, economic, social, and political disturbances caused by climate change (Tanner et al., 2015; Clare et al., 2017; Tyler and Moench, 2012; Tyler et al., 2016). This builds on the literature and concepts of disaster resilience that have emerged from the original ecological concept of resilience, first introduced by Holling (1973). Although resilience as a concept is not new, its meaning and application for decision-making is often unclear and various definitions and frameworks have been developed to transfer resilience from a concept to something tangible and applicable to decision-making and planning in the climate and disaster risks space. Among these are definitions that consider the multi-dimensional nature of resilience: determinants of resilience include a combination of social, financial, physical, political, human and natural factors that interact with one another to determine how an entity (e.g. household, community, city, country, etc.) responds to shocks and stresses (Keating et al., 2017b; Keating et al., 2017a; Campbell et al., 2019; Torabi et al., 2018). Moreover, it has been widely discussed that resilience is not binary—i.e. it exist or it doesn't—(Southwick et al., 2014) but that instead it may be present to different degrees across multiple domains and risks. For example, a city that is known to be resilient to flood risks may not be resilient to urban heat issues. In addition, resilience is not fixed but a continually changing process that depends on developments in cities and changes of risks—defined as evolutionary resilience by Davoudi et al. (2012). Therefore, there is a general consensus that resilience should not be seen as a state or outcome but a dynamic process and set of conditions embodied within a system (Norris et al., 2008; Mitchell and Harris, 2012). In fact, Carpenter et al. (2001) described resilience as a measurable quantity that can be assessed only after specifying 'resilience of what to what and for whom'. To address such complex, dynamic and context-specific definitions of resilience, "resilience measurement" concepts, frameworks and tools have been developed to assist our understanding of 'holistic' resilience in each specific context.

Over the last decade many international initiatives and humanitarian organizations such as the World Resources Institute, ARUP, UN office for Disaster Risk Reduction, and Asian Cities Climate Resilience Network, together with national and regional governments have collaborated with cities across the world and developed versions of resilience indicators to measure resilience of households, communities, cities, regions, or countries against extreme weather events and

---

[1] Hereafter we use 'climate resilience' and 'resilience' interchangeably.

wider physical impacts of climate change. Some of these tools are location and hazard-specific while others have an all-hazards, multi-community and multi-cultural approach for measuring resilience (Ostadtaghizadeh et al., 2015). Many review studies have consequently been developed to analyse the common conceptual and methodological hurdles and opportunities of such tools (Sharifi and Yamagata, 2016; Sharifi, 2016; Asadzadeh et al., 2017; Saja et al., 2019; Cai et al., 2018; Brown et al., 2018). Despite all the effort on analysing and improving the methodological aspects of such tools, what is less clear is how resilience measurement tools can actually support decision making for enhancing urban climate resilience. In other words: to what extent can resilience measurement tools be or have been utilized by city-level actors to support their decision-making process for building climate resilience?

In this study, we examine:

- RQ1: If and how the suite of resilience measurement tools supports *decision-making* toward building climate resilience in cities (Content and implementation process of tools).
- RQ2: How the use of such tools has influenced resilience *actions* in cities and what the challenges and opportunities of building resilience have been (End-users experiences and insights).

To answer the first question, we systematically analyse 27 urban resilience measurement tools using the decision-making cycle and resilience capacities frameworks. To answer the second question, we assess results from 12 key-informant interviews with experts who were involved in implementation of four of the most widely applied tools across the world. It should be noted that this study does not set out to evaluate the methodological and underlying conceptualization of resilience measurement tools, but it is specifically focused on supporting resilience decision-making and actions in response to urban climate risks. There are several papers providing meta-analysis of tools on the methodological and conceptual elements that readers can refer to—see studies cited above.

Section 2 provides conceptual frameworks we adopted and used for analysing the content and implementation process of tools. Sections 3 explains the data collection and analysis methods. Section 4 presents the results of our analysis, and finally, section 5 discusses findings and offers concluding thoughts.

2. Conceptual frameworks

To analyse if and how resilience measurement tools are supporting decision-making toward building resilience (RQ1) we rely on the literatures on decision-making and resilience theories and employ two conceptual frameworks as described below.

2.1. Decision cycle

Decision theory literature frames the pathway from identifying problems to implementing actions as a decision cycle shown in figure 1. It starts with identifying the main problems and criteria that may constrain decision-making processes (i.e., formal and informal rules), and is followed by the ex-ante assessment of alternative actions, selecting and implementing actions, and finally ex-post evaluation and monitoring of actions. This is ideally an iterative process with internal feedback loops among different stages, thus, it does not always follow the circle steps in an orderly fashion. This decision cycle has been widely adopted and discussed in disaster and climate risk management studies (McDermott and Surminski, 2018; Mechler et al., 2019; IIASA & Zurich, 2015; Swart et al., 2021) yet not all its stages are commonly applied in practice. While there has been a great deal of effort in developing methods and providing data for the first three steps (particularly data on the level of probability and severity of future hazards, vulnerability, exposure, and resilience of communities) what often remains challenging is the implementation of actions, and ex-ante and ex-post evaluation and monitoring of measures i.e., stages 4 and 6 (Surminski and Leck, 2017).

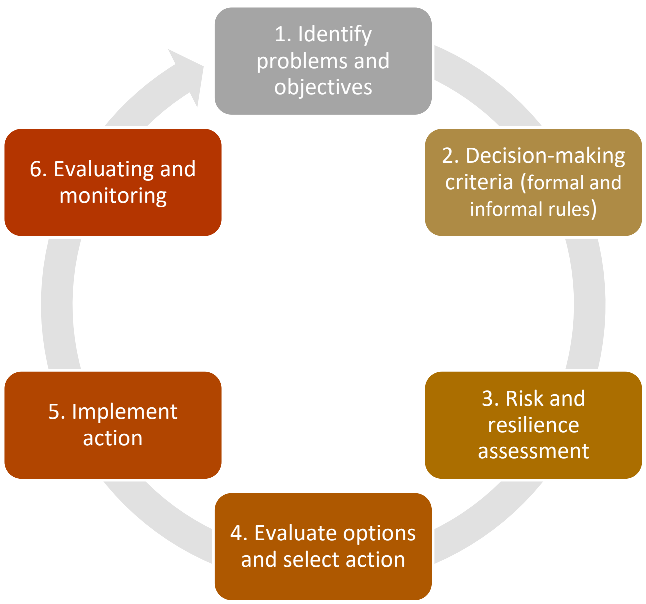


Figure 1. Different stages of the 'decision cycle' widely adopted for climate adaptation and disaster risk reduction decision-making studies – adopted from McDermott and Surminski (2018), IIASA & Zurich (2015), and CLIMATE-ADAPT Urban Adaptation Support Tool of the European Environment Agency, see https://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast/step-0-0.

As Surminski and Leck (2017) explain, in the context of urban climate decision-making, stages 1-3 are more focused on agenda-setting, planning, knowledge sharing and raising awareness, while stages 4-6 are aimed at implementing solutions and delivering actions. Transitioning from agenda setting to implementation is reported as the core of urban resilience discourse, where, after a period of evidence collection and analysis, actors are facing the challenge of implementing solutions (Surminski and Leck, 2017). McDermott and Surminski (2018) argue that even in cities with great access to accurate data on climate risk and resilience (stage 3), what often determines if and what action is taken is the normative interpretation of this information by urban decision-makers and their political judgements. This has led to growing interest in more innovating ways of supporting the implementation phase of the decision cycle for climate resilience.

2.2.Three elements of decision-making enabling urban climate resilience

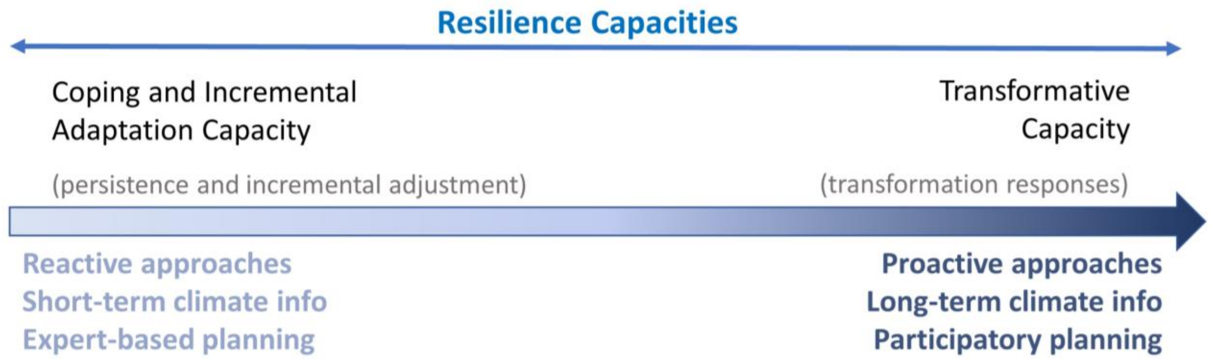
Resilience is traditionally defined in social-ecological systems as the ability to deal with the impacts of adverse changes and shocks (Gunderson, 2000). In theory, this ability includes ‘shock absorbing and coping’, as well as ‘evolving and adapting’ and ‘transforming’ (Walker et al., 2002; Folke et al., 2010). Making a city resilient, similarly, is increasingly recognized in conceptual studies as developing plans, programs, and strategies that improve the capacity of communities to cope with, adapt to, and transform in the face of potential threats and changes (Khazai et al., 2015). In practice, however, resilience thinking and resilience practices have been challenged for promoting an incremental approach to coping and adaptation that does not fully recognize the need for change and transformation in the rapidly changing cities, and therefore, reinforce the status quo and existing vulnerabilities (Keating and Hanger-Kopp, 2020). While coping and incremental adaptation strategies assist returning to the ‘pre-shock situation’, transformation strategies facilitate ‘adjusting to the new impacts of climate change’, and ‘creating a new system’ when the existing system is untenable or undesirable (Engle et al., 2014). In the latter, “resilience” practice might aim not to maintain the system’s current identity (in this case cities’ form, structure, processes, and strategies) but, rather, improve it (Orleans Reed et al., 2013).

While the difference between transformation and incremental adaptation may not always be clear-cut, some recent studies have attempted definitions: For example, Kates et al. (2012) describe three classes of transformational measures - those that are truly new to a region or system, those that transform places and shift locations, and those that are adopted at a much larger scale or intensity. Through a systematic review of existing literature, Deubelli and Mechler (2021) conclude that for an intervention to qualify as ‘transformational’ in the context of climate risk management and adaptation, it should result in large-scale, profound and deep-rooted changes in the society or cities, challenging the status quo, generating long-term impacts, and re-framing priorities and preferences (Wilson et al., 2020; Fedele et al., 2019).

In the context of urban climate risk and resilience, it is insufficient to rely on conventional strategies that helping people to cope or incrementally adapt to climate change. Such an approach is unsustainable, or even maladaptive (Fedele et al., 2019; Park et al., 2012; Colloff et al., 2021). Indeed, many scholars have shown that vulnerabilities and risks related to climate change are becoming so sizeable that novel and transformational interventions are more than ever needed (Kates et al., 2012; Wilson et al., 2020; Fedele et al., 2019). This also highlights the merits of transformational measures for coping and adaptation capacities: as transformational actions work on the root causes of problems and vulnerabilities; they can reduce risks to a level that societies can cope with and adapt to.

We draw on well-established research on transformational decision-making (see citations in following sub-sections) to unpack some of the elements of decision-making that can foster transformative capacities versus those that perpetuate coping and incremental adaptation capacities in the context of climate change (figure 2).

Figure 2: Three elements of decision-making that trigger or hinder transformation in the context of climate change – adapted from Béné et al. (2014)



Proactive approaches: To increase transformative capacities, cities need to take proactive approaches in addressing climate risks, which foster forward thinking and innovative solutions (Quay, 2010; Park et al., 2012; Malekpour et al., 2015; Mehryar and Surminski, 2020; Birchall et al., 2021). Proactive strategies actively strive to minimise risks by reducing exposure and vulnerability to climate impacts in urban areas. In other words, a proactive approach does not wait for external events to respond to, but instead "anticipate opportunities for transformation, and disrupt the system from within to bring about large-scale changes" (Novalia and Malekpour, 2020). In the context of urban climate resilience, proactive strategies are associated with ex-ante activities that are used to either reduce *existing* risks (called *corrective risk reduction*) or avoid the development of new or increased risks in future (called *prospective risk reduction*) (Mehryar and Surminski, 2021). For example, employing climate-smart urban planning may enforce a land-use change in areas exposed to increasing weather extremes, in order to avoid locating people and infrastructure in these areas and thereby increasing risks (i.e., prospective risk reduction), while building flood walls and retrofitting of critical infrastructures help to reduce the existing flood risks for assets and population already at risk (i.e., corrective risk reduction). On the contrary, a purely reactive strategy would focus on increasing coping capacity to respond and recover from specific crises. Whilst providing the response and recovery measures in the aftermath of catastrophic events is important, prioritization of such short-term reactive over proactive measures can lead to accelerating the "status quo" over the long run (Novalia and Malekpour, 2020).

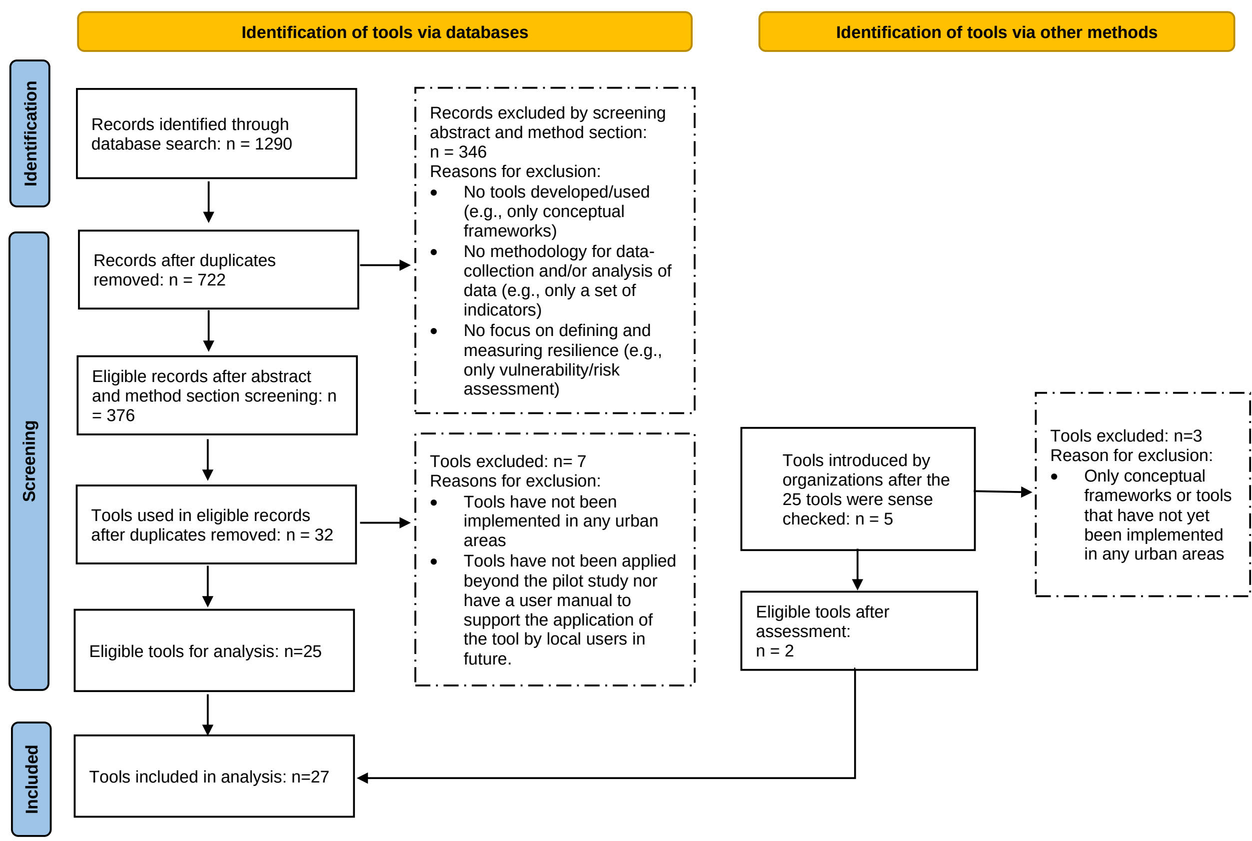
Long-term climate information use: Recognizing and taking account of climate change impacts is an important enabler of planning for transformation. Long-term climate projections provide useful information on climate and weather trends, and possible exposure to hazards in the future. Climate services provide science-based climate information and knowledge to support climate-smart decision-making at all levels of society (Vaughan and Dessai, 2014). A report published by LTS and DFID (2020) argues that access to and use of long-term climate information can support uptake of transformative measures in accordance with the future climate variability, whereas replying on short-term climate information such as 1-14 day or seasonal weather forecasting can only support short-term coping and incremental adaptation measures. Advances in historical observation, data processing, and computer modelling over the last three decades have led to an expansion of available climate information and services, from seasonal weather forecasts to decadal and multi-decadal climate change projections (Soares et al., 2018). However, the provision, contextualization, and uptake of this information amongst urban climate-sensitive sectors (e.g., infrastructure, urban planning, health) is often reported to be inadequate or challenging (Lemos et al., 2012; Hewitt et al., 2017; Jones et al., 2017; Golding et al., 2017).

Participatory planning: Transformation involve significant changes in thinking from the individual to the organizational level (Rickards et al., 2014). Participatory planning (i.e., based on involving various types of stakeholders in the process of analysing problems and designing, implementing, and evaluating solutions) facilitates social learning and enhances understanding of subsequent transformational changes. Participatory planning can also foster the multi-sectoral collaboration and collective decision-making required for long-term transformation (Fedele et al., 2019). The diversity of perspectives gathered in a participatory planning setting is generally recognized in the literature as an important aspect of learning and transformative capacity (Pelling et al., 2015; Broto et al., 2019).

Therefore, we argue that decision-making processes that include these three elements, i.e., proactive approach, climate information use, and participatory planning, are more likely to motivate building transformative capacity, and hence, resilience to growing urban climate risks. We acknowledge that building resilience is a complex process and there are multiple factors influencing decision-making for resilience and transformation. Some other important factors and enablers of transformation are, for example, related to the leadership, organizational structures, and institutions such as re-framing values, rules, knowledge, will, and mindset of relevant actors (Torabi et al., 2018; Wilson et al., 2020; Colloff et al., 2021). However, in this study we only include those elements that can be evaluated and supported by resilience measurement tools in the process of decision-making, i.e., content of decisions (proactive approach), the way decisions are made (participatory approach), and type of knowledge used (climate information). These three decision-making elements may not guarantee but lack of them hamper building or enhancing resilience, and particularly transformative capacities.

3. Methods and data collection

We identified and analysed 27 resilience measurement tools[2] developed for assessing climate resilience of cities across the world (see table 2). "Web of Science", "Google Scholar" and "Google" were used to collect both scientific and non-scientific documents referring to any of these tools. A combination of "climate/hazard/disaster" AND "resilience" AND "measurement/assessment" AND "tool/toolkit/index/matrix/indicator" were used as search strings. This search also included hazard-specific tools (e.g., flood resilience measurement tools) so long as they have one of the climate/hazard/disaster words in their documents. Although not all hazard/disaster tools have been developed to particularly address 'climate' resilience, we still included them as they are generally being used to measure resilience to the acute shocks (e.g., flooding) and chronic stresses (e.g., drought) caused or developed by climate change. In addition, our data collection results were then sense checked with experts from Mercy Corps, ISET-international and the Zurich Flood Resilience Alliance (who have worked on the review and analysis of existing resilience measurement tools) to make sure a full list of relevant tools were included. The process of identifying and selecting tools from the databases and organizations together with the reasons for exclusion of tools and their publications can be seen in figure 3.



[2] We use the term "tool" to refer to all types of assessment schemes that include a set of indicators or parameters defined for measuring resilience and a methodology for collecting and/or analysing data. Different developers may use different terms such as tools, toolkit, index, scorecard, or framework.

Figure 3. process of identifying and selecting tools from databases and organizations, adapted from the preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram.

Additionally, semi-structured key-informant interviews were conducted with 12 practitioners and government members who have been involved in implementation of four of the most widely applied tools in over 100 cities, in total. The selection of interviewees was done in a way to ensure cross-representation and recognition of geographic, governance and socio-economic balance in the use and application of tools. In addition, as the aim of interviews were to gather insights on the application of resilience measurement tools (in general) in decision-making, the interviewees were selected among those who were involved in applying at least one of the tools in many different cities across the world. The overarching themes of the interview discussions were:

1- What were the main impacts of applying resilience measurement tools in cities you worked with?
2- If and how the results of tools have been used to support taking actions toward resilience?
3- What have been the most important barriers/challenges in implementing an intervention based on the measurement results?

More information about the interviewees, their affiliation, tools they used, and cities/countries in which they applied the tools can be seen in Supplementary 1. Themes emerged in more than one interview together with the number of interviewees mentioned each theme are presented and discussed in section 4.3.

We acknowledge that the small number of interviews could be a limitation of this study. For the purpose of this research, we have selected end-users who have implemented tools in a variety of cities (average of 11 cities per interviewees) to get insight on application of tools across various contexts and locations. However, we admit that involving more key informants in the interviews could include broader experiences and more diverse knowledge on the application of tools which would require a separate study. In addition, interviews are only focused on application of four tools which are the most applied tools across the world. It should, therefore, be noted that these interviews are meant to provide an understanding of the role of the general resilience measurement practices in the process of decision-making. Yet, a tool-specific analysis would require interviewing end-users of all tools being analysed and comparing the role of different tools in the process of decision-making.

Content analysis criteria: based on the two frameworks presented in section 2, we analysed to what extent the 27 tools support

a) the six stages of the decision-making cycle, particularly those focused on implementation (stages 4-6) in addition to awareness (stages 1-3), and

b) the three elements of decision-making that foster transformational actions, as set out in figure 2.

We reviewed the manuals or methodology sections of each tool to identify how the resilience measurement results can be used for decision-making and implementing actions. In particular, we explore whether a tool measures resilience and informs decision-makers (stages 1-3 of decision cycle) or whether the tool also advises on selection of actions (stage 4), implementing (stage 5), and evaluation and monitoring the actions (stage 6). For the second part of the content analysis, we reviewed and examined the tools' indicators/parameters and methodologies used to measure resilience by applying the following analysis criteria (Table 1):

Table 1: Criteria for analysing tools

Element of decision-making for climate resilience	Criteria for analysing tools
Proactive approach	*Corrective & Prospective Risk reduction*: Are risk reduction measures/activities being recognized (measured) as well as the response/recovery measures/activities?
Climate information use	*Climate change indicator*: do the tools have any indicator/parameter/question on climate change and its impacts?
	Climate info use in methodology: are climate change predictions and scenarios being used in the process of measuring resilience?
Participatory planning	*Participatory planning indicator*: do the tools have any indicator on participatory approach in planning and decision-making?
	Participatory approach in methodology: is participatory approach being used in the process of measuring resilience?

Corrective & Prospective Risk reduction: To identify **proactive approaches**, we assessed whether the 27 tools include indicators/parameters/questions to evaluate *prospective* and *corrective risk reduction* strategies in cities as per descriptions in section 2.2 (i.e., proactive strategies to avoid or reduce future risks) in addition to response and recovery (i.e., reactive strategies used for coping with future risks).

Climate change indicator & climate information use in methodology: to assess **climate information use**, we analysed if and how the 27 tools 1) include any indicator/parameter/question to evaluate level of climate change awareness and climate information use by local stakeholders, and 2) use climate scenarios and predictions as a part of their methodology to assess resilience of communities against future risks.

Participatory planning indicator & participatory approach in methodology: to assess **participatory planning**, we analysed if and how the 27 tools 1) include any indicator to measure community participation in the process of decision-making for resilience building in cities, and 2) take a participatory approach in their methodology to collect and analyse data for measuring urban climate resilience.

4. Results

Among the 27 tools identified, 11 tools were found to be specifically developed for urban areas, while the remaining 16 tools are applicable in both urban and non-urban areas. These 27 tools have been developed by academia (n=13), international organizations or multi-organization collaborations (n=10), and national governments and consultancies (n=4). 16 of these tools were specifically initiated by (i.e., developed on the request of) national governments (e.g., the US EPA) or international philanthropic organizations (e.g., the Rockefeller Foundation and Z Zurich Foundation). Interestingly, only 3 tools are specifically designed to measure climate resilience (MONARES and EURCC), or climate and disaster resilience (CDRI[1]), and others measure resilience to disasters and hazards that are impacts of climate change. Among the tools analysed, 8 tools measure resilience to *climate-related hazards* (including both acute shocks and long-term stresses), 16 tools measure resilience to *all hazards* including climate and non-climate-related hazards (e.g., earthquake, volcano, etc.), and 3 tools measure resilience to single hazards, i.e., all acute shocks: flooding, and coastal hazards such as tsunamis, storms, and shoreline erosion. Although most of the tools have been developed and introduced as universally applicable, only 7 of them have been so far implemented and tested across different continents. Among these 7 tools, CRI, DSRSC, FRMC, CRPT and RIT have been implemented worldwide through a collaboration between the developers of tools and local partners, whereas BRIC and CART have been implemented mainly by end-users independently.

Table 2: overview of the 27 tools developed and used for measuring urban climate resilience.

Tool	Year of the first release	Developer	End users	Copyright/ ownership	Resilience to what?	Urban only?	Implementation areas by developer	Nr of independent applications by users	Ref
Bassline Resilience Indicators for Communities (BRIC)	2010	academia	National/local governments, planners	Can be implemented by users independently	Climate-related hazards	no	Entire USA counties	+10	link
The Australian Natural Disaster Resilience Index (ANDRI)	2015	academia (initiated by the national government)	Planners, emergency service providers, state fire departments	Can be implemented by users independently	Climate-related hazards	no	Entire Australia	0	link
Coastal Community Resilience (CCR)	2007	multi-orgs (initiated by USAID)	communities, NGOs, planners, government	Can be implemented by users independently	Coastal hazard	no	Indian ocean coasts	1	link
Disaster Resilience Index (DRI)	2015	multi-orgs	National/local government agencies	Can be implemented by users independently	All-hazards	yes	6 cities in developing countries	0	link
PEOPLES	2010	Academia (initiated by	Planners, local authorities	Has only been used by developer	All-hazards	no	4 cities in the USA	0	link

		the US Federal government)							
City Resilience Index (CRI)	2015	ARUP (initiated by Rockefeller Foundation)	Local authorities	Can only be used in collaboration w tool developers	All-hazards	yes	80 cities worldwide	1	link
ICLEI-ACCCRN Process	2008	ICLEI/ ACCCRN	Local authorities	Can only be used in collaboration w tool developers	Climate-related hazards	yes	46 Asian cities	0	link
Climate and disaster resilience initiative (CDRI[1])	2010	multi-orgs	City gov officials	Can only be used in collaboration w tool developers	Climate-related hazards	yes	8+ Asian cities	2	link
Natural Hazard Resilience Screening Index (NaHRSI)	2017	EPA	US County authorities	Has only been used by developer	All-hazards	no	Entire USA counties	0	link
Communities Advancing Resilience Toolkit (CART)	2013	academia	Community organizations	Can be implemented by users independently	All-hazards	no	2 case studies (1 urban & 1 non-urban) in the USA	7	link
Community Disaster Resilience Index (CDRI[2])	2010	Academia (initiated by the national government)	Unclear	Can be implemented by users independently	All-hazards	no	144 counties in the USA gulf coast	2	link
Community Disaster Resilience Scorecard Toolkit (CDRST)	2014	Torrens resilience institute (initiated by the national government)	Communities and planners	Can be implemented by users independently	All-hazards	no	9 communities in Australia	2	link
The Conjoint Community Resiliency Assessment Measure (CCRAM)	2013	academia	Local authorities	Can be implemented by users independently	All-hazards	no	+10 communities in 2 cities in Israel	1	link
Disaster Resilience Scorecard for Cities (DRSC)	2014	Multi-orgs (initiated by UNDRR)	Local authorities	Can only be used in collaboration w tool developers	All-hazards	yes	214 cities worldwide	2	link
Enhancing resilience of communities and territories facing natural and na-tech hazards (ENSURE)	2011	academia	Local authorities, planners	Can be implemented by users independently	All-hazards	no	3 regions in Greece, Israel and Italy	0	link

Monitoring adaptation measures and climate resilience in cities (MONARES)	2019	Adelphi Germany (initiated by the national government)	Local authorities, planners	Can be implemented by users independently	Climate-related hazards	yes	Ongoing – implementation not completed yet	0	link
Resilience Inference Measurement (RIM)	2015	academia	Unclear	Can be implemented by users independently	Climate-related hazards	no	52 counties in the USA	2	link
ResilSIM	2016	academia	Planners, emergency services	Has only been used by developer	Flooding	yes	2 cities in Canada	0	link
Urban Community Resilience Assessment (UCRA)	2019	WRI	Unclear	Can only be used in collaboration w tool developers	All-hazards	yes	3 cities in Brazil, Indonesia & India	0	link
Flood Resilience Measurement for Communities (FRMC)	2013	Multi-orgs (initiated by Z Zurich foundation)	NGOs, local authorities, planners and managers	Can only be used in collaboration w tool developers	Flooding	no	+300 communities in 20 countries worldwide	0	link
ARC-D TOOLKIT	2016	GOAL	NGOs, local authorities, planners and managers	Can be implemented by users independently	All-hazards	no	+225 communities in 13 developing countries	0	link
Evaluating Urban Resilience to Climate Change (EURCC)	2017	EPA	local level managers	Has only been used by developer	Climate-related hazards	yes	2 cities in the USA	0	link
Composite Disaster Resilience Index ($CDRI^3$)	2019	academia	NGOs, local authorities, planners and managers	Can be implemented by users independently	Climate-related hazards	no	Entire Italy	0	link
Los Angeles County Community Disaster Resilience Project (LACCDR)	2016	Research institute (initiated by the sub-national government)	LA county authority and planners	Has only been used by developer	All-hazards	no	Los Angeles county	0	link
Resilience Assessment Benchmarking and Impact Toolkit (RABIT)	2016	academia	Developing country strategists and practitioners	OA, developer provides training, unclear	All-hazards	no	1 city in Costa Rica & 1 rural district in Uganda	0	link
City resilience profiling tool (CRPT)	2018	UN Habitat	Local authorities, planners	Can only be used in collaboration w tool developers	All-hazards	yes	6 Cities worldwide	0	link
Resilience Insight Tool (RIT)	2016	Buro Happold Consultancy -	City governments, international	Can only be used in collaboration	All-hazards	yes	12 cities worldwide	0	link

		BRE centre for resilience	bodies and planners	w tool developers					

4.1.Decision cycle

The first part of our analysis explored the application of the above tools in the context of the different phases of the decision cycle. Figure 4 shows the findings: identifying problems and objectives, and decision-making criteria (e.g., whether to invest in and prioritize community flood resilience) mostly happen internally within organizations. The resilience measurement tools that we analysed support stages 3-6 of decision cycle, some of which only focus on stage 3 (assessing the level of resilience that is the main objective of these tools) while others support multiple stages of decision cycle.

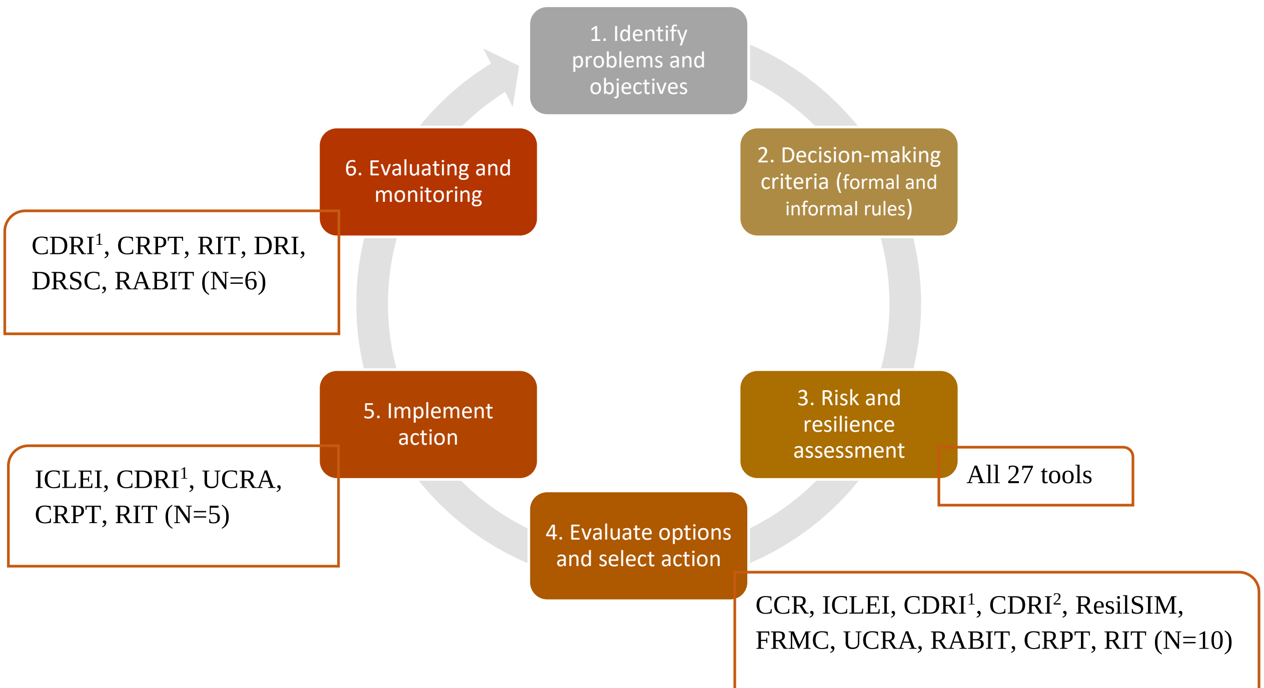


Fig 4: Tools supporting different stages of decision cycle.

Risk and resilience assessment: All the resilience measurement tools analysed utilise an indicator-based approach in which resilience is measured via a set of indicators or components covering various social, political, human, ecological, financial, and physical aspects of resilience. Some tools also recommend conducting a risk assessment at the beginning of the process to identify the level and distribution of exposure to hazard impacts and ensure the most important risks are being considered for the resilience measurement. DRSC, for example, prompts city stakeholders to identify "most probable" and "most severe" risk scenarios for single or multi-hazard events using the Quick Risk Estimation tool developed by UNDRR and Deloitte. ICLEI includes a subjective risk assessment methodology which assists prioritizing risks through a participatory and inclusive process. Although not many tools include a risk assessment process, it is widely acknowledged that for mapping out a path toward climate and multi-hazard resilience, it is essential to first obtain a comprehensive understanding of the locations, levels, and types of risks a city faces.

Most of the tools analysed (15 out of 27) are focused ‘only’ on assessing resilience (stage 3 of the decision cycle). In such tools, resilience indicators that score low are often interpreted as the most urgent challenges requiring interventions. However, decision-making about what actions can and should be taken and when depends on more complex environmental and contextual variables that should be considered.

The other 12 tools go beyond the resilience assessment stage and are explicitly designed to support other stages of a decision cycle such as options appraisal, implement actions, and evaluation and monitoring (stages 4-6)—see table 3.

Table 3: Evaluation criteria for assessing how resilience measurement tools support decision-making and planning for urban climate resilience. ✓= addressed, ✗ = not addressed or not enough information provided.

Tool	Decision-cycle stage(s)	Repeated measurement (achieved in practice)	Proactive approaches		Long-term climate info use		Participatory planning	
			Corrective Risk reduction	Prospective risk reduction	Climate change indicator(s)	Climate change information use in methodology	Participatory planning indicator(s)	Participatory approach in methodology
BRIC	3	✓	✗	✗	✗	✗	✓	✗
ANDRI	3	✗	✓	✓	✗	✗	✓	✓
CCR	3&4	✗	✓	✓	✓	✗	✓	✓
DRI	3&6	✗	✓	✓	✗	✗	✓	✓
PEOPLES	3	✓	✗	✗	✗	✗	✗	✓
CRI	3	✗	✓	✓	✗	✗	✓	✓
ICLEI	3,4&5	✗	✓	✗	✓	✓	✓	✓
CDRI[1]	3,4,5 & 6	✗	✓	✓	✓	✗	✗	✓
NaHRSI	3	✗	✗	✗	✗	✗	✗	✗
CART	3&4	✗	✗	✗	✗	✗	✗	✓
CDRI[2]	3	✗	✓	✓	✗	✗	✗	✗
CDRST	3&6	✓	✗	✗	✗	✗	✓	✓
CCRAM	3	✗	✗	✗	✗	✗	✗	✓
DRSC	3	✗	✓	✓	✓	✗	✓	✓
ENSURE	3	✗	✗	✗	✗	✗	✗	✓
MONARES	3	✗	✗	✗	✓	✗	✓	✓
RIM	3	✗	✗	✗	✗	✗	✗	✗
ResilSIM	3&4	✗	✗	✗	✗	✗	✗	
UCRA	3,4&5	✗	✗	✗	✓	✓	✓	✓
FRMC	3&4	✓	✓	✗	✓	✗	✓	✓
ARC-D	3	✗	✓	✓	✓	✗	✓	✓
EURCC	3	✗	✓	✓	✓		✗	✓
CDRI[3]	3	✗	✗	✗	✗	✗	✗	
LACCDR	3	✓	✗	✗	✗	✗	✗	✓
RABIT	3,4&6	✗	✓	✓	✓	✓	✗	✓
CRPT	3,4,5&6	✗	✓	✗	✗	✓	✓	✓
RIT	3,4,5&6	✓	✗	✗	✓	✓	✗	✓

Option appraisal: 10 tools support evaluating resilience building options prior to their implementation (stage 4) via a range of analysis and methods. ICLEI's tool, for instance, evaluates and prioritizes resilience interventions based on their 1) feasibility (availability of technical expertise, relevant roles and responsibilities, political will, and financial capacity), 2) expected impacts (significant short, medium, and long term impact on the targeted climate risk), as well as their alignment with characteristics of resilience (i.e. redundancy, resourcefulness, robustness, and rapidity). An important aspect of options appraisal being considered in the ICLEI tool is the integration of recommended interventions into existing city plans. This is particularly important as cities often have a comprehensive set of plans, ongoing programs, and projects at any one time. Success of the resilience projects depends on their alignment to the core vision and overarching programs of cities. In this phase, thus, local decision-makers can integrate the identified resilience strategies into existing departmental workplans. This also avoids duplications and wasted efforts.

CDRI[1], CRPT, RIT, FRMC, and UCRA, on the other hand, evaluate and prioritize interventions and strategies via stakeholder workshops by using self-evaluation criteria and metrics developed by stakeholders. CRPT applies scenario processes to explore evolution of urban systems under three scenarios: current, trend, and the resilience scenarios. The current scenario is built upon the existing risk, exposure, and vulnerability of cities, the trend scenario includes the ongoing plans, programs, and projects of cities, and the resilient scenario is built upon the actions recommended as a result of the resilience assessment. RIT also utilizes scenario building to test the potential impacts of different strategies for increasing resilience capacities against the current baseline. This also enables insight into the costs and benefits of different options and for them to be compared with the cost of inaction.

ResilSIM is the only tool that applies a modelling and simulation method to support ex-ante evaluation of interventions by simulating the possible impacts of interventions in the model prior to actual implementation.

Implementing actions: Following stage 4, some tools go further and support developing a short- and long-term resilience plan and program to facilitate the implementation of resilience interventions, as well as to support long-term city resilience planning. While stage 4 (i.e., options appraisal) evaluates the availability and access to crucial capacities and resources, stage 5 (i.e., implementing actions) focuses on creating or improving capacities and resources required for implementing resilience actions. CRPT, UCRA, RIT, CDR[1] and ICLEI, for example, generate a complete and detailed roadmap of the stakeholders, responsibilities, institutional mechanisms, technical support, policy changes or fund raising needed for the implementation of the identified resilience strategies. In UCRA, the local partners then submit their resilience plan to the relevant departments within the city to determine the next steps. This is also another step, in which decision-makers can further align the resilience projects and strategies with the key city planning objectives to maximise the chances of success and return on investments (e.g., in UCRA).

Evaluation and monitoring: There are a few tools developed particularly to support monitoring and evaluating the impacts of cities' activities on climate resilience. Some of these tools take a benchmarking approach in which progresses of cities in building or enhancing resilience (as a whole, not as individual measures/actions) is measured against a set of pre-defined goals or standards. DRSC, for instance, assists local governments in monitoring and reviewing progress and challenges in the implementation of the Sendai Framework for Disaster Risk Reduction: 2015-2030. It is, therefore, structured around UNDRR's ten essentials for making cities resilient. DRI, similarly, establishes benchmarks and evaluates progress on the mainstreaming of risk reduction and resilience approaches in the cities' development policies and processes.

CRPT, RIT, CDRI[1] and RABIT, on the other hand, have a project-based approach, meaning specific monitoring and evaluation criteria are developed in each action plan to measure the progress of that project/intervention over time (i.e., if and how the project is satisfying its specific pre-defined goals). RABIT is particularly designed to support practitioners in developing countries to evaluate and monitor the impact of their development interventions on community resilience. This tool requires practitioners to identify how each individual project will be/has been contributing to the different attributes of resilient systems either during the initial set-up of goals for interventions or after the implementation of interventions. The former establishes the key areas of focus in each intervention to build resilience, while the latter informs future planning/decision-makings based on lessons learned.

Additionally, many tools recommend that the resilience measurement be repeated over time in order to monitor and evaluate changes. However, only a few of the tools have actually been implemented more than once (e.g., BRIC, FRMC, CDRST, LACCDR, RIT and PEOPLE – see table 3). However, if a tool is applied repeatedly over time, it does not automatically mean that it serves as a monitoring and evaluation process in and of itself. Overall, comparing various aspects of resilience at different time periods and associating them with specific intervention remains a challenging task, particularly given the qualitative and subjective nature of data collection methods used in such tools. Thus, most of the tools remain one-off measures in most of the cities, which does not support understanding of the evolutionary nature of resilience and monitoring impacts of resilience interventions.

4.2. Enablers of transformative decision-making

The second part of our analysis explored which resilience capacities (i.e., coping, incremental adaptive and transformative capacities) the tools support and how (figure 2). Our analysis revealed that most of the tools particularly lack recognition of proactive approaches and climate information use in assessing resilience of cities. Therefore, some tools may influence transformational decision-making more than others by providing insights and recommendations on proactive strategies, long-term climate information use, and participatory planning (table 4). Content of the tools identified as per each element and criterion can be seen in supplementary 2.

Table 4: Tools supporting different enablers of transformative decision-making. Percentages represent the proportion of the tools that incorporate each element.

Enablers of transformative decision-making	Tools incorporating each element
Proactive approaches	ANDRI, CCR, DRI, CDRI[1], DRSC, ARC-D, EURCC (25%)
Long-term climate info use	ICLEI, UCRA, RABIT, RIT (14%)
Participatory planning	ANDRI, CCR, DRI, CRI, ICLEI, CDRST, DRSC, MONARES, UCRA, FRMC, ARC-D, CRPT (44%)

Proactive strategies: Among the tools analysed, we only found 7 tools that have a strong focus on proactive strategies for cities to reduce impacts of climate change (i.e., EURCC, ANDRI, CCR, DRI, CDRI[1], DRSC, and ARC-D). These 7 tools have adopted different types of indicators/parameters/questions to measure various aspects of risk reduction including corrective and prospective risk reduction in addition to post-event response and recovery. While both corrective and prospective risk reduction strategies support proactive and ex-ante risk reduction and adaptation, prospective risk reduction measures are key in enabling transformation capacities of cities. Indicators used in these 7 tools to measure prospective risk reduction strategies of cities are generally focused on:

- The application of smart and adaptive architecture and urban design/planning (e.g., multi-functional landscapes for urban flood control and urban tree canopy cover, green roofs, urban ventilation, and tree shading programs to lessen urban heat island effects),
- incorporation of DRR and adaptation in existing urban plans and policies (e.g., zoning, land use, and urban development plans), urban design (e.g., urban morphology, urban green space, and sustainable drainage system), building codes, and resilient housing,
- incentives for the implementation of prospective risk reduction measures (e.g., government mechanisms to purchase lands on floodplains and financial support for integrating green infrastructure into urban infrastructure planning), and
- enforcement mechanisms (e.g., insurance mechanisms that explicitly discourage rebuilding of properties on floodplains)

Among these 7 tools, DRI, CDRI[1], DRSC, and ARC-D were developed based on the Sendai Framework for Disaster Risk Reduction and the UNDRR's 10 essentials for making cities resilient, all of which focus on prioritizing pro-active risk reduction and adaptation strategies. These 7 tools also assess the human and social capacities of communities which can influence prospective risk reduction behaviour in the long run. For example, education and training programs for improving 1) awareness around current and future risk, and 2) compliance with risk reduction policies and principles.

Long-term climate information: Surprisingly, out of the 27 tools, only 11 tools include at least one indicator that assesses understanding of climate change or utilization of climate change information/scenarios in city planning (table 3). UCRA and FRMC, for example, measure level of perceived climate risk (i.e., impact of climate change on future risks) by communities. ARC-

D, CCR and DRSC have indicators that assess the extent to which local authorities have access to and use existing climate information to inform local decision-making. RABIT assesses whether local communities have access to climate change awareness training and educational resources. CDR[1] assesses incorporation and mainstreaming of climate change uncertainties and adaptation in cities' disaster risk management planning, land use and environmental plans, housing and transportation policies, and school education curriculum. MONARES evaluates the climate change adaptation aspect in city development plans as well as the existence of climate change working groups in local governments. This tool also measures whether ICTs used to inform local decision-making processes also facilitate access to different types of climate change information e.g., projections and forecasts.

Some tools such as ICLEI, NaHRSI, RABIT, UCRA, and RIT support local governments in developing climate exposure projections and applying them in their resilience assessments. Climate information used for such projections includes information on past climate-related events and future climate change trends and projections. ICLEI provides local governments with detailed guidance on the potential climate data sources and the process of collecting and analysing the data. NaHRSI utilizes the climate information provided by the National Climate Assessment and 100 Resilient Cities report together with discussions with climate change experts in regional agencies. RIT utilizes climate exposure projections to measure the changing resilience demand over a period of 15 years (2015-2030). Projections are based on various models provided by OPCC, IMF, WHO, United Nations, OECD, and HM ONS. It is, however, well acknowledged that the projection horizon year for each city/country depends on the availability of climate data and that the further into the future the projection is made, the less confidence can be placed in the results (Collins et al., 2013).

In addition, ICLEI and ARC-D include scenario building with local stakeholders as a part of the resilience assessment process which helps identifying and planning for future climate risks and dealing with uncertainties. ARC-D, for instance, utilized the climate scenarios and identifies the priority risk scenarios based on the prioritization of shocks and stresses, the exacerbating effect of stresses on shocks, the degree of loss and damage caused by the shocks and the communities' coping capacity to overcome this. In any given assessment in the field, the user can choose one multi-hazard risk scenario or up to two single-hazard risk scenarios (i.e., assess two different hazards in the same assessment).

Participatory planning: 21 of tools apply at least one type of public engagement method to collect primary data for measuring resilience (e.g., household survey, key informant interview and focus group discussion). 12 of this subset apply a combination of interviews, workshops, and surveys to maximize the community engagement during the process. At the same time, 13 tools are found that evaluate the level of community participation in the local decision-making and planning of cities (table 3). Such measures include assessing citizen participation in 1) disaster awareness and capacity building training and education (e.g., DRR and adaptation awareness activities), 2) rating and assessing risks, vulnerabilities, and resilience, 3) decision-making for

DRM and climate adaptation interventions, and 4) developing, implementing, and monitoring plans, policies, and programs.

In addition, 6 tools (i.e., CART, CDRI[2], CDRI[3], ENSURE, RABIT and PEOPLES) rely solely on measuring the level of community engagement in social networks and society activities. Such engagements are usually used as proxies to assess the level of community access to emergency warnings and information and the level of community assistance in the emergency response phase (Menoni et al., 2012; Parker and Handmer, 1998)—i.e. only short-term adaptation and response activities. Long-term transformational adaptation and DRR activities, though, require direct engagement of communities in city planning and programming.

4.3. Does measurement of resilience lead to resilience actions?

Finally, we reflect on key-informants' perspectives to assess if and how resilience measurement tools have been actually used to support decision-making. The 12 key-informants were involved in implementation of four of the most widely applied tools, i.e., ICLEI, DRSC, CRF, and FRMC, in over 100 cities across the world. Drawing on our key informant interviews, we elaborate on 1) the impacts of applying such tools on the decision-making process, 2) if and what resilience actions have been taken as a result of measuring resilience, and 3) barriers and challenges of taking resilience actions recommended by tool. It should be noted that interviews were not set out to evaluate quality and credibility of each individual tool for supporting decision-making. Instead, the aim of interviews was to gain insights (base on practical examples) on how the whole concept of measuring resilience can support local decision-making and taking actions for urban climate resilience.

Impacts on decision-making process

Most of the key informants argued that resilience measurement tools are supposed to encourage resilience thinking and prioritizing resilience activities in the process of decision-making rather than providing solutions for decision-makers. Therefore, they pointed out some of the less tangible but long-term impacts of resilience measurement activities on decision-making (based on their experiences and observations) as follows:

Providing a holistic view of risk and resilience: 9 out of 12 interviewees highlighted that gathering various sorts of data in one place and evaluating resilience through different capitals/systems was a major benefit of using resilience measurement tools, which would have not been normally considered by the city actors (due to lack of access to information or resources). "Using the tools have particularly encouraged a focus on the social and natural aspects of resilience that are often neglected under the shadow of the physical and hydrological aspects" (KI7). Many interviewees argued that such holistic thinking was brought about by the functionality of tools that allow inputting different perspectives, knowledge, and data from various stakeholders and sectors (KI1, 2, 3, 5&8). This also encourages system-thinking among the city actors: "The process definitely brought new questions into the decision-makers minds, if nothing else, about what needs to be done apart from what they had always focused on" (KI3).

Increasing public engagement and awareness: 8 interviewees argued that the process of implementing tools lead to an increase in public engagement in the decision-making process for climate resilience and raising awareness about the level and locations of climate risks. This is particularly the case for the tools that have a participatory approach in collecting and evaluating data. In some cities this has been identified as best practice that should be replicated in future decision-making processes. "With or without the tool they would have built the dam any way (…), but what they did after implementing the tool was that they did a lot of public hearings and meetings and talking to the residents about their ideas and concerns over this project, which was suggested by tool (KI)"

Supporting understanding resilience as more than a vague concept: 6 interviewees also highlighted the role of tools in helping city actors to familiarize themselves with climate and disaster resilience through tangible measures relevant to their local context. This has particularly claimed to be effective in tools that link resilience to frameworks that local decision-makers are already familiar with and work with, such as the disaster risk management cycle, risk reduction and adaptation targets and sustainable development goals, facilitating understanding and application of resilience in a day-to-day decision-making process (KI1,10,11,12).

Familiarizing city actors with uncertainty and unexpected changes: Finally, 2 interviewees explained how the focus of resilience measurement tools on uncertainties caused by climate change supported city actors to realise the need for transformative decision-making rather than incremental planning and management. "Measuring resilience and identifying resilience challenges often shows that building resilience is about the long-term uncertain future that cities need to be prepared for, whereas most of the information supporting decisions being made are based on the historical data or short-term projections" (KI1&4).

What actions have been taken?

The interviewees also explained a few avenues by which resilience measurement results led to tangible actions/interventions; below we outline the most common outcomes:

Strategies and policies: 6 interviewees described at least 15 cities that used resilience measurement tools and their results to inform the creation or update of strategies, policies, and guidance reports. In most of such cases, the creation of strategies was not the direct output of the tool, rather, the tool and its results triggered or facilitated discussions around including urban resilience components into existing policy documents (e.g., in Santa Fe, Argentina, Addis Ababa, and Houston). This has been particularly impactful in countries where city level stakeholders (i.e., the main users of tools) had the power to influence national level debates on policy developments.

Informing urban planning and design: In addition to policies and strategies, two interviewees particularly pointed out how the resilience measurement results have also been used in three cities to inform and improve the urban and spatial planning and design of cities: the city of Manchester used results of CRI analysis to inform their cycling and walking, and in San

Francisco, US and Amadora, Portugal results were used to improve city master plans by adding more green space and avoiding development projects in the risk prone areas.

Increase investments: in 22 cities described by 8 interviewees, the tools results were used to support funding applications or to allocate and reallocate local budgets for implementing resilience projects recommended by the tools (e.g., in Cilacap, Indonesia; Irga city in Philippines; greater Manchester, UK; Java, Indonesia; Lowestoft, UK; and many cities in Mongolia). In some countries, implementing resilience measurement was a requirement for cities wishing to apply for funding whereas in others it has been a proactive approach of city governments (KI11).

Connecting and sharing information with other cities: 5 interviewees argued that many cities also used the outcomes of tools to share their experiences and learn from other cities who applied the same tool. This was particularly the case in the UNDRR and 100 Resilient Cities programs, where a network of cities was already established before the development of the tools (i.e., DRSC and CRI) which accelerated sharing information and learnings among the cities involved in the program. Cross-national connections of urban information via city networks have been shown to accelerate opportunities for proactive and well-informed decision-making (Acuto, 2018; Hughes et al., 2020).

Challenges and barriers for resilience actions

In addition to the content of tools that may or may not support resilience building (as described in section 4.2), there are some environmental and contextual barriers and challenges which can hinder or constrain implementation of resilience actions. Our end-user interviews revealed five main barriers and challenges for building resilience found in various cities and countries. These are:

Prioritisation of most recent risks: 10 out of 12 interviewees mentioned that existence of other city priorities, including city development programs, and coping with the most recent risks, often take the attention of city governments away from climate risk reduction and adaptation activities. This is particularly the case in cities facing low frequency-high severity risks of climate change such as severe flood events that may not occur often, but when they do, have profound consequences. “The biggest obstacle is when, for example, in Semarang (Indonesia) you try to convince local government to plant mangroves in the riverside which may impact half a million people but then you get big businessmen coming with their hotel and shopping centre projects with tens of millions of dollars financial benefits for the city. They can easily wipe your progresses out (…)” (KI4). “A recent and clear example is the COVID-19 pandemic emergency which has acutely overshadowed governments plans and programs for climate adaptation.” (KI1) It has also been discussed that governments that focus mainly on emergency response, coping and protection strategies are more likely to have a short-term reactive response, and as a result, suddenly shift their focus from existing long-term risks to the most recent and urgent risks (KI1, 4, 5, 6, 12).

Top-down governance system and lack of local power: Six of the interviewees who have worked with cities in countries that have a centralized government system mentioned that the local authorities in such cities have little or no power to change plans and policies or (re)allocate financial and human resources toward new activities, and therefore, have little responsibility and accountability for the creation or mitigation of risks related to climate change and disasters. In such circumstances, "…the city governments are less willing to consider transformative decisions and actions in favour of continuing with the business-as-usual strategies defined by the central government".

Political instability: Three of the interviewees who have worked with cities experiencing frequent and significant turn-over in the national and/or local leadership argued that such instabilities does not allow for the establishment of the long-term transformational strategies required for building resilience (KI 1& 11). Such political instability at the national and city government levels is a consequence of political infighting for the gain of political party over others, rather than a focus on meeting the needs of communities (Pasquini et al., 2015). Political instability leads to frequent changes and redirection of municipal actions and resources (and therefore, loss of human capacity built in past periods), replacement of public actors based on their political alignments rather than expertise, and more importantly, incapability of municipalities to develop and implement long-term strategies (Pasquini et al., 2015; Nightingale, 2017).

Lack of transparency: Three interviewees argued that city governments with low transparency are generally less willing to publicly communicate gaps and limitations, acknowledge and act upon them, whereas cities with transparent and open government systems often take a self-critical approach to assessing and communicating the outcomes of their activities with the public, and therefore, are more likely to uptake different and transformative measures (change the land use of flood prone areas, invest on green infrastructure instead grey infrastructure, etc.). It has also been acknowledged that the implementation of resilience actions is only possible through the partnership of the local and political leaders willing to bring about change and transformation in their city planning and governance systems.

Rigid departmentization: As resilience is a multi-dimensional concept, improving city resilience requires addressing multiple systems and multi-sectoral challenges (i.e., related to social, human, natural, physical and financial systems) which calls for a strong collaboration and coordination among different public sectors and departments within a city. However, a lack of a whole-of-government approach and cross-cutting cooperation among different sections of a city government have been highlighted by two interviewees as another crucial barriers in implementing resilience interventions. "This particularly becomes a deterrent factor in implementing resilience interventions when there are different and sometimes conflicting interests, preferences, and priorities across different sectors" (KI4).

Therefore, it is important to recognize that even the most advanced resilience measurement tools can still face institutional and organizational challenges. Proper utilization of decision-support tools prerequires agents and institutions that are shaped and shifted toward creating transformation for building resilience (Torabi et al., 2018).

5. Conclusion

Resilience measurement tools have been developed, implemented, and studied for a long enough time that they can be now evaluated for their application in supporting decision-making. In this paper, we found that only about a third of existing urban resilience measurement tools support implementation at any stages (i.e., option appraisal, implementation planning, and monitoring and evaluation). In order to support resilience action, it is important to acquire a deep understanding of the governance system and structure, human and financial resources and the formal and informal norms and rules in each context. This can also help facilitate an effective integration of resilience thinking into the existing action planning of cities.

Moreover, building resilience is about enhancing coping, adaptive and transformative capacities altogether so that the most relevant and effective strategies can be used at each stage of urban climate risk management. However, our analysis shows that most of the urban resilience tools analysed are designed in such a way to evaluate and, thereby, encourage coping and incremental adaptation capacities rather than transformative capacities. Out of 27 tools analysed, 20 tools have a primary focus on measuring response and recovery activities (i.e., reactive strategies) and 16 tools do not include any climate change impacts in their analysis, and therefore, measure resilience only based on current climate risks. This lack of recognition of proactive risk reduction measures and the disregard of future climate change impacts are likely to lead to prioritisation of quick fix solutions instead of pointing towards the longer-term resilience interventions.

Our analysis shows that most of the urban resilience measurement tools incorporate participatory approaches for assessing resilience and/or evaluating the decision-making process of cities. This is a positive sign and indicates a general understanding of the complexity and subjective aspects of resilience which require engagement of a variety of stakeholders for evaluation of and decision-making for a change. Participatory planning can not only help to generate awareness but also buy-in and support for implementing measures aiming at creating deliberate and significant change while also helping to ensure that measures are targeted and in line with community needs. However, different levels and types of participation can lead to different resilience pathways. While project level inclusion of actors and society (e.g., discussion on building a flood wall which is already funded and planned) can only support incremental adaptation to flood risks, program level participation of society (e.g., discussion on and planning for various aspects of flood resilience) can lead to transformational decision-making. Therefore, tools that apply participatory approach in collecting evidence (see table 3) and supporting decision-making for broader resilience interventions and strategies (see section 4.1. Option appraisal) are more likely to facilitate transformational decisions and actions than those rely on expert knowledge and/or only involve actors and society for specific projects. By contrast, tools that only involve society ate the project-level implementation, evaluation, and monitoring (i.e., stages 4-6 of the decision cycle) may take the risk of perpetuating incremental actions.

While we acknowledge that there is no perfect tool, we encourage users and developers to have a close look at the frameworks and approaches of tools identified in this research with strong consideration of proactive strategies, climate information use, and participatory planning. We acknowledge that having these three elements in the process of decision-making might not guarantee but could encourage transformational decisions and actions over incremental ones. Importantly there are also wider factors that influence decision-making in the municipal context: National and local governance structures, human and financial resources, political will and interests, and priority of most recent risks were mentioned as the most important contextual barriers for implementing resilience actions. Transition from resilience assessment to resilience action, therefore, requires consideration of such contextual aspects in evaluation and selection of solutions. Future studies could explore this in greater detail to help inform design and implementation of transformative decision-making support tools. This would ideally include the resources, process, roles, and actors needed for such a transition. In addition, further research is required to study how the conceptual and methodological differences of tools (e.g., framework and types of indicators used, data collection methods, using qualitative and quantitative data, unite of measurement, single-hazard vs multi-hazard, grading methods, subjective vs objective evaluation of measures, etc.) may impact an effective decision-making process.

Acknowledgment: We are grateful for peer review comments and feedback from Dr Candice Howarth and Dr Adriana Keating on earlier version of this paper.

Funding: This work was supported by the Z Zurich Foundation, Switzerland; the Grantham Foundation for the Protection of the Environment and the ESRC via the Centre for Climate Change Economics and Policy under Grant number: ES/R009708/1.

References:

ACUTO, M. 2018. Global science for city policy. *Science,* 359**,** 165-166.

ARGÜESO, D., EVANS, J. P., FITA, L. & BORMANN, K. J. 2014. Temperature response to future urbanization and climate change. *Climate dynamics,* 42**,** 2183-2199.

ASADZADEH, A., KÖTTER, T., SALEHI, P. & BIRKMANN, J. 2017. Operationalizing a concept: The systematic review of composite indicator building for measuring community disaster resilience. *International journal of disaster risk reduction,* 25**,** 147-162.

BELLINSON, R. & CHU, E. 2019. Learning pathways and the governance of innovations in urban climate change resilience and adaptation. *Journal of environmental policy & planning,* 21**,** 76-89.

BÉNÉ, C., NEWSHAM, A., DAVIES, M., ULRICHS, M. & GODFREY-WOOD, R. 2014. Resilience, poverty and development. *Journal of International Development,* 26**,** 598-623.

BIRCHALL, S. J., MACDONALD, S. & SLATER, T. 2021. Anticipatory planning: Finding balance in climate change adaptation governance. *Urban Climate,* 37**,** 100859.

BROTO, V. C., TRENCHER, G., IWASZUK, E. & WESTMAN, L. 2019. Transformative capacity and local action for urban sustainability. *Ambio,* 48**,** 449-462.

BROWN, C., SHAKER, R. R. & DAS, R. 2018. A review of approaches for monitoring and evaluation of urban climate resilience initiatives. *Environment, development and sustainability,* 20**,** 23-40.

CAI, H., LAM, N. S., QIANG, Y., ZOU, L., CORRELL, R. M. & MIHUNOV, V. 2018. A synthesis of disaster resilience measurement methods and indices. *International journal of disaster risk reduction,* 31**,** 844-855.

CAMPBELL, K. A., LAURIEN, F., CZAJKOWSKI, J., KEATING, A., HOCHRAINER-STIGLER, S. & MONTGOMERY, M. 2019. First insights from the Flood Resilience Measurement Tool: A large-scale community flood resilience analysis. *International Journal of Disaster Risk Reduction,* 40**,** 101257.

CARPENTER, S., WALKER, B., ANDERIES, J. M. & ABEL, N. 2001. From metaphor to measurement: resilience of what to what? *Ecosystems,* 4**,** 765-781.

CLARE, A., GRABER, R., JONES, L. & CONWAY, D. 2017. Subjective measures of climate resilience: what is the added value for policy and programming? *Global Environmental Change,* 46**,** 17-22.

COLLINS, M., KNUTTI, R., ARBLASTER, J., DUFRESNE, J.-L., FICHEFET, T., FRIEDLINGSTEIN, P., GAO, X., GUTOWSKI, W. J., JOHNS, T. & KRINNER, G. 2013. Long-term climate change: projections, commitments and irreversibility. *Climate Change 2013-The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

COLLOFF, M. J., GORDDARD, R., ABEL, N., LOCATELLI, B., WYBORN, C., BUTLER, J. R., LAVOREL, S., VAN KERKHOFF, L., MEHARG, S. & MÚNERA-ROLDÁN, C. 2021. Adapting transformation and transforming adaptation to climate change using a pathways approach. *Environmental Science & Policy,* 124**,** 163-174.

DAVOUDI, S., SHAW, K., HAIDER, L. J., QUINLAN, A. E., PETERSON, G. D., WILKINSON, C., FÜNFGELD, H., MCEVOY, D., PORTER, L. & DAVOUDI, S. 2012. Resilience: a bridging concept or a dead end?"Reframing" resilience: challenges for planning theory and practice interacting traps: resilience assessment of a pasture management system in Northern Afghanistan urban resilience: what does it mean in planning practice? Resilience as a useful concept for climate change adaptation? The politics of resilience for planning: a cautionary note: edited by Simin Davoudi and Libby Porter. *Planning theory & practice,* 13**,** 299-333.

DEUBELLI, T. M. & MECHLER, R. 2021. Perspectives on transformational change in climate risk management and adaptation. *Environmental Research Letters,* 16**,** 053002.

ENGLE, N. L., DE BREMOND, A., MALONE, E. L. & MOSS, R. H. 2014. Towards a resilience indicator framework for making climate-change adaptation decisions. *Mitigation and Adaptation Strategies for Global Change,* 19**,** 1295-1312.

FEDELE, G., DONATTI, C. I., HARVEY, C. A., HANNAH, L. & HOLE, D. G. 2019. Transformative adaptation to climate change for sustainable social-ecological systems. *Environmental Science & Policy,* 101**,** 116-125.

FOLKE, C., CARPENTER, S. R., WALKER, B., SCHEFFER, M., CHAPIN, T. & ROCKSTRÖM, J. 2010. Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and society,* 15.

GARSCHAGEN, M. & ROMERO-LANKAO, P. 2015. Exploring the relationships between urbanization trends and climate change vulnerability. *Climatic Change,* 133**,** 37-52.

GOLDING, N., HEWITT, C., ZHANG, P., BETT, P., FANG, X., HU, H. & NOBERT, S. 2017. Improving user engagement and uptake of climate services in China. *Climate Services,* 5**,** 39-45.

GRIMMOND, S. U. 2007. Urbanization and global environmental change: local effects of urban warming. *Geographical Journal,* 173**,** 83-88.

GUNDERSON, L. H. 2000. Ecological resilience—in theory and application. *Annual review of ecology and systematics,* 31**,** 425-439.

HANSON, S., NICHOLLS, R., RANGER, N., HALLEGATTE, S., CORFEE-MORLOT, J., HERWEIJER, C. & CHATEAU, J. 2011. A global ranking of port cities with high exposure to climate extremes. *Climatic change,* 104**,** 89-111.

HEWITT, C. D., STONE, R. C. & TAIT, A. B. 2017. Improving the use of climate information in decision-making. *Nature Climate Change,* 7**,** 614-616.
HOLLING, C. S. 1973. Resilience and stability of ecological systems. *Annual review of ecology and systematics,* 4**,** 1-23.
HUGHES, S., GIEST, S. & TOZER, L. 2020. Accountability and data-driven urban climate governance. *Nature Climate Change***,** 1-6.
HUGHES, S. & SARZYNSKI, A. 2015. Building capacity for climate change adaptation in urban areas: Editors' introduction. *Urban Climate***,** 1-3.
IIASA & ZURICH 2015. Turning knowledge into action: processes and tools for increasing flood resilience. Zurich, Switzerland: Zurich Insurance Company.
JONES, L., CHAMPALLE, C., CHESTERMAN, S., CRAMER, L. & CRANE, T. A. 2017. Constraining and enabling factors to using long-term climate information in decision-making. *Climate Policy,* 17**,** 551-572.
KATES, R. W., TRAVIS, W. R. & WILBANKS, T. J. 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences,* 109**,** 7156-7161.
KEATING, A., CAMPBELL, K., MECHLER, R., MAGNUSZEWSKI, P., MOCHIZUKI, J., LIU, W., SZOENYI, M. & MCQUISTAN, C. 2017a. Disaster resilience: what it is and how it can engender a meaningful change in development policy. *Development Policy Review,* 35**,** 65-91.
KEATING, A., CAMPBELL, K., SZOENYI, M., MCQUISTAN, C., NASH, D. & BURER, M. 2017b. Development and testing of a community flood resilience measurement tool. *Natural Hazards and Earth System Sciences,* 17**,** 77-101.
KEATING, A. & HANGER-KOPP, S. 2020. Practitioner perspectives of disaster resilience in international development. *International Journal of Disaster Risk Reduction,* 42**,** 101355.
KHAZAI, B., BENDIMERAD, F., CARDONA, O. D., CARREÑO, M.-L., BARBAT, A. H. & BUTON, C. 2015. A guide to measuring urban risk resilience: Principles, tools and practice of urban indicators. *Earthquakes and Megacities Initiative (EMI), The Philippines*.
LEICHENKO, R. 2011. Climate change and urban resilience. *Current opinion in environmental sustainability,* 3**,** 164-168.
LEMOS, M. C., KIRCHHOFF, C. J. & RAMPRASAD, V. 2012. Narrowing the climate information usability gap. *Nature climate change,* 2**,** 789-794.
LTS AND DFID 2020. Enabling Climate Science Use to Better Support Resilience and Adaptation Practice. Edinburgh, Scotland: LTS International Limites (UK).
MALEKPOUR, S., BROWN, R. R. & DE HAAN, F. J. 2015. Strategic planning of urban infrastructure for environmental sustainability: Understanding the past to intervene for the future. *Cities,* 46**,** 67-75.
MARSCHÜTZ, B., BREMER, S., RUNHAAR, H., HEGGER, D., MEES, H., VERVOORT, J. & WARDEKKER, A. 2020. Local narratives of change as an entry point for building urban climate resilience. *Climate Risk Management,* 28**,** 100223.
MCDERMOTT, T. & SURMINSKI, S. 2018. How normative interpretations of climate risk assessment affect local decision-making: an exploratory study at the city scale in Cork, Ireland. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 376**,** 20170300.
MECHLER, R., MCQUISTAN, C., MCCALLUM, I., LIU, W., KEATING, A., MAGNUSZEWSKI, P., SCHINKO, T., LAURIEN, F. & HOCHRAINER-STIGLER, S. 2019. Supporting climate risk management at scale. Insights from the zurich flood resilience alliance partnership model applied in Peru & Nepal. *Loss and Damage from Climate Change.* Springer.
MEEROW, S., NEWELL, J. P. & STULTS, M. 2016. Defining urban resilience: A review. *Landscape and urban planning,* 147**,** 38-49.

MEHRYAR, S. & SURMINSKI, S. 2020. The role of national laws in managing flood risk and increasing future flood resilience. *Grantham Research Institute on Climate Change and the Environment, London School of Economics*.
MEHRYAR, S. & SURMINSKI, S. 2021. National laws for enhancing flood resilience in the context of climate change: potential and shortcomings. *Climate Policy,* 21**,** 133-151.
MENONI, S., MOLINARI, D., PARKER, D., BALLIO, F. & TAPSELL, S. 2012. Assessing multifaceted vulnerability and resilience in order to design risk-mitigation strategies. *Natural Hazards,* 64**,** 2057-2082.
MI, Z., GUAN, D., LIU, Z., LIU, J., VIGUIÉ, V., FROMER, N. & WANG, Y. 2019. Cities: The core of climate change mitigation. *Journal of Cleaner Production,* 207**,** 582-589.
MITCHELL, T. & HARRIS, K. 2012. Resilience: A risk management approach. *ODI background note***,** 1-7.
NIGHTINGALE, A. J. 2017. Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum,* 84**,** 11-20.
NORRIS, F. H., STEVENS, S. P., PFEFFERBAUM, B., WYCHE, K. F. & PFEFFERBAUM, R. L. 2008. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American journal of community psychology,* 41**,** 127-150.
NOVALIA, W. & MALEKPOUR, S. 2020. Theorising the role of crisis for transformative adaptation. *Environmental Science & Policy,* 112**,** 361-370.
ORLEANS REED, S., FRIEND, R., TOAN, V. C., THINPHANGA, P., SUTARTO, R. & SINGH, D. 2013. "Shared learning" for building urban climate resilience–experiences from Asian cities. *Environment and Urbanization,* 25**,** 393-412.
OSTADTAGHIZADEH, A., ARDALAN, A., PATON, D., JABBARI, H. & KHANKEH, H. R. 2015. Community disaster resilience: A systematic review on assessment models and tools. *PLoS currents,* 7.
PARK, S. E., MARSHALL, N. A., JAKKU, E., DOWD, A. M., HOWDEN, S. M., MENDHAM, E. & FLEMING, A. 2012. Informing adaptation responses to climate change through theories of transformation. *Global Environmental Change,* 22**,** 115-126.
PARKER, D. J. & HANDMER, J. W. 1998. The role of unofficial flood warning systems. *Journal of contingencies and crisis management,* 6**,** 45-60.
PASQUINI, L., ZIERVOGEL, G., COWLING, R. M. & SHEARING, C. 2015. What enables local governments to mainstream climate change adaptation? Lessons learned from two municipal case studies in the Western Cape, South Africa. *Climate and Development,* 7**,** 60-70.
PELLING, M., O'BRIEN, K. & MATYAS, D. 2015. Adaptation and transformation. *Climatic Change,* 133**,** 113-127.
QUAY, R. 2010. Anticipatory governance: A tool for climate change adaptation. *Journal of the American Planning Association,* 76**,** 496-511.
RICKARDS, L., WISEMAN, J., EDWARDS, T. & BIGGS, C. 2014. The problem of fit: scenario planning and climate change adaptation in the public sector. *Environment and Planning C: Government and Policy,* 32**,** 641-662.
ROSENZWEIG, C., SOLECKI, W. & HAMMER, S. 2010. Cities lead the way in climate–change action. *Nature* 467**,** 909-911.
SAJA, A. A., GOONETILLEKE, A., TEO, M. & ZIYATH, A. M. 2019. A critical review of social resilience assessment frameworks in disaster management. *International journal of disaster risk reduction,* 35**,** 101096.
SHARIFI, A. 2016. A critical review of selected tools for assessing community resilience. *Ecological indicators,* 69**,** 629-647.
SHARIFI, A. & YAMAGATA, Y. 2016. On the suitability of assessment tools for guiding communities towards disaster resilience. *International journal of disaster risk reduction,* 18**,** 115-124.

SINGH, C., MADHAVAN, M., ARVIND, J. & BAZAZ, A. 2021. Climate change adaptation in Indian cities: A review of existing actions and spaces for triple wins. *Urban Climate,* 36**,** 100783.
SOARES, M. B., ALEXANDER, M. & DESSAI, S. 2018. Sectoral use of climate information in Europe: A synoptic overview. *Climate Services,* 9**,** 5-20.
SOUTHWICK, S. M., BONANNO, G. A., MASTEN, A. S., PANTER-BRICK, C. & YEHUDA, R. 2014. Resilience definitions, theory, and challenges: interdisciplinary perspectives. *European journal of psychotraumatology,* 5**,** 25338.
SURMINSKI, S. & LECK, H. 2017. From agenda-setting to implementation: The role of multisectoral partnerships in addressing urban climate risks. *Earth's Future,* 5**,** 966-978.
SWART, R., CELLIERS, L., COLLARD, M., PRATS, A. G., HUANG-LACHMANN, J.-T., SEMPERE, F. L., DE JONG, F., COSTA, M. M., MARTINEZ, G. & VELAZQUEZ, M. P. 2021. Reframing climate services to support municipal and regional planning. *Climate Services,* 22**,** 100227.
TANNER, T., LEWIS, D., WRATHALL, D., BRONEN, R., CRADOCK-HENRY, N., HUQ, S., LAWLESS, C., NAWROTZKI, R., PRASAD, V. & RAHMAN, M. A. 2015. Livelihood resilience in the face of climate change. *Nature Climate Change,* 5**,** 23-26.
TORABI, E., DEDEKORKUT-HOWES, A. & HOWES, M. 2018. Adapting or maladapting: Building resilience to climate-related disasters in coastal cities. *Cities,* 72**,** 295-309.
TYLER, S. & MOENCH, M. 2012. A framework for urban climate resilience. *Climate and development,* 4**,** 311-326.
TYLER, S., NUGRAHA, E., NGUYEN, H. K., VAN NGUYEN, N., SARI, A. D., THINPANGA, P., TRAN, T. T. & VERMA, S. S. 2016. Indicators of urban climate resilience: A contextual approach. *Environmental science & policy,* 66**,** 420-426.
VAUGHAN, C. & DESSAI, S. 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change,* 5**,** 587-603.
WALKER, B., CARPENTER, S., ANDERIES, J., ABEL, N., CUMMING, G., JANSSEN, M., LEBEL, L., NORBERG, J., PETERSON, G. D. & PRITCHARD, R. 2002. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. *Conservation ecology,* 6.
WILSON, R. S., HERZIGER, A., HAMILTON, M. & BROOKS, J. S. 2020. From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nature Climate Change,* 10**,** 200-208.
WOLFF, C., NIKOLETOPOULOS, T., HINKEL, J. & VAFEIDIS, A. T. 2020. Future urban development exacerbates coastal exposure in the Mediterranean. *Scientific reports,* 10**,** 1-11.