Integrating solutions to adapt cities for climate change

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Record climate extremes are reducing urban liveability, compounding inequality, and threatening infrastructure. Adaptation measures that integrate technological, nature-based, and social solutions can provide multiple co-benefits to address complex socioecological issues in cities while increasing resilience to potential impacts. However, there remain many challenges to developing and implementing integrated solutions. In this Viewpoint, we consider the value of integrating across the three solution sets, the challenges and potential enablers for integrating solution sets, and present examples of challenges and adopted solutions in three cities with different urban contexts and climates (Freiburg, Germany; Durban, South Africa; and Singapore). We conclude with a discussion of research directions and provide a road map to identify the actions that enable successful implementation of integrated climate solutions. We highlight the need for more systematic research that targets enabling environments for integration; achieving integrated solutions in different contexts to avoid maladaptation; simultaneously improving liveability, sustainability, and equality; and replicating via transfer and scale-up of local solutions. Cities in systematically disadvantaged countries (sometimes referred to as the Global South) are central to future urban development and must be prioritised. Helping decision makers and communities understand the potential opportunities associated with integrated solutions for climate change will encourage urgent and deliberate strides towards adapting cities to the dynamic climate reality.

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Cities confronting unprecedented climate challenges

Extreme weather events are increasingly common across cities on every continent.[1] Climate records in 2019 have chronicled widespread heatwaves across the northern and southern hemispheres.[2] Wildfires induced by climate change devastated cities and towns in California, Chile, and Australia during 2018 and 2019,[3] and at the same time more extreme precipitation patterns are increasing both urban drought and flood risk.[4] Rising sea levels, coupled with other environmental issues in coastal cities, have triggered environmental and social change with no historical parallel.[5] Current climate change models predict that the mean maximum temperature in cities globally will increase by 2–8°C in just a few decades, with cities in Europe, South America, and Africa potentially facing stronger and more frequent droughts, exacerbating current water scarcity and crises.[6]

Today more than half of the world's population lives in cities, with the proportion of urban residents set to rise to over 70% by 2070.[7] The increased focus on cities over the past decade, coupled with the challenges that climate change will certainly bring about, has encouraged a large push by all scales of governments to generate activities, innovations, and transformative changes to help cities address the impacts of climate change.[8,9] These actions have proven to be insufficient, and there is a clear need to help decision makers think strategically about layering adaptation solutions within cities that can lead to greater resilience across multiple potential futures.[10]

Integrating diverse adaptation measures will be required to realise the transformations needed to build resilience to climate change and protect urban infrastructure and communities. This Viewpoint aims to spur a discussion on how to systematically integrate three types of solutions (ie, technological, nature-based, and social solutions), to strengthen urban climate resilience, and outline ways for overcoming the range of challenges that hamper integration. We present three case studies with different limitations and contexts of decision making to highlight diverse approaches. Finally, we describe how integration might enable long-term and fundamental change.

Major types of urban solutions

A large body of evidence supports the relevance of a range of technological, nature-based, and social solutions to adapt cities to climate challenges, but the question remains as to how best to integrate these different, but complementary, solutions to maximise benefits. We present a summary of each solution type, indicate what some of the main benefits are, consider the challenges and enablers that might exist to integrate them, and then present three short case studies to show how integration has occurred and how challenges were overcome to achieve multiple goals related to sustained mitigation and adaptation.

Urban technological solutions

Technological solutions for adapting cities to climate change are well studied, and new technologies are continually emerging and examined for their overall efficacy. For example, air conditioning is considered a protective factor for health during heatwaves, but changes towards systems-based heating and cooling that take advantage of cooling towers or district distribution can save energy and reduce sensible heat discharge.[11] Simple technological solutions have also been widely adopted to help cities create more resilient systems.[12] Building materials that increase the albedo of

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urban surfaces to reflect sunlight, such as light-coloured paint, can reduce the heat load of buildings during summer,[13] and permeable pavements that replace asphalt can mitigate urban heat and stormwater runoff by reflecting radiation, providing evaporative cooling, and allowing underlying soil to absorb precipitation.[14] Increasingly, big data and internet-of-things tools can inform decision makers in real time to make more effective decisions on resource needs and flows in cities. Sensors and automated or unmanned systems (eg, on-demand watering systems) are increasingly common under smart-cities frameworks to save, recycle, and upcycle water before or during droughts and floods.[15,16] Although technological solutions are well studied and new solutions are continually developed or improved, they remain out of reach for many cities without the resources to implement and maintain them. Often, technological solutions require social and governmental intervention to overcome barriers of implementation.[17,18]

Urban nature-based solutions

Nature-based solutions (ie, the use of vegetation and blue-green infrastructure), can provide a multitude of ecosystem services, such as improving the environment and delivering health and wellbeing outcomes.[19,20] Increasingly, nature-based solutions have been adopted to help alleviate problems such as extreme heat, drought, or flooding.[21,22] Tree cover is often used to cool transportation corridors, and regional tree cover can itself influence mesoclimatic patterns.[23] In flood-prone cities, bioswales along streets or constructed wetlands in newly built suburbs help to regulate vertical and horizontal hydrological flows.[24]

However, urban nature-based solutions are sensitive to many of the climate challenges they are meant to address because changes in temperature and precipitation will affect green infrastructure itself.[25] For example, reduced water availability to support trees and their canopy might lead to a rapid decline in shade cover, transpiration, and evaporative cooling.[26] For this reason, nature-based solutions require adequate management to maintain their desired functions and performances as the environment changes.[27] The resilience of urban vegetation must, therefore, be planned under alternative future climate change scenarios to ensure that the benefits can continue to be delivered.[28,29] Although gaining increasing attention from researchers and practitioners, it remains unclear to what extent nature-based solutions are comparable with, and thus can replace, grey infrastructure in terms of effectiveness.[30] Nature-based solutions, when implemented at scale, can have major financial and governance challenges.[31]

Urban social solutions

Social solutions to climate change are based on examining shifts in social values that encourage individuals to change their behaviours and practices.[32] These solutions can increase acceptance and adoption of new or previously uncomfortable measures.[33] Social mobilisation initiatives, from government-led planning processes to neighbourhood-scale grassroots initiatives, can lower perceived barriers around sustainable climate solutions and motivate action through engagement, learning, and hands-on involvement.[34] Many social solutions aim to reduce inequality and impact on vulnerable groups of people, such as those who might have fewer resources for technological solutions (eg, air conditioning), less access to cooler private or public green spaces, as well as less access to information for adaptation.[35] In cities with a large number of poor communities, awareness of climate risk might be high but the ability to self-protect can be limited.[36] Political disenfranchisement or isolation might further exacerbate risks from climate change if groups are not involved in decision-making processes regarding adaptation and mitigation.[37]

Existing patterns of vulnerability highlight the need to consider structural inequality in designing incentives, public engagement, and emergency plans that do not exacerbate or compound existing inequality. Strategies such as building alliances between municipal and local institutions might be necessary to incentivise collaboration across regional processes (eg, transportation networks, water systems, and land use policies).[38] Strategic roles, such as network brokers, can link disconnected or disenfranchised groups, to ensure that all stakeholders are heard and knowledge is shared and co-produced.[39]

The value of integration

Individual solution types are unable to address the complexity and scale of climate change adaptation in cities. The different qualities of the individual solution types, when integrated, can provide the necessary components to enable structural or systemic transformation, while ensuring that the focus is not too narrow with specific or one-dimensional outcomes.[40] For example, although air conditioning provides a protective factor from high temperatures, social solutions such as changing the culture of an office to allow for more casual work attire or shifting operating hours to cooler times to reduce energy use can also reduce carbon emissions.[41] Technological flood protection, such as dikes or pumping stations, will be enhanced by nature-based solutions, such as beach nourishments, waterfront renaturing, or wetlands, to protect cities from wave action while also providing valuable spaces for recreation and biodiversity conservation.[42]

Another example of a sector that would benefit greatly from the integration of solution types is urban transportation. For example, developing public and active transport systems (eg, walking and cycling pathways) that use permeable pavements and are shaded by

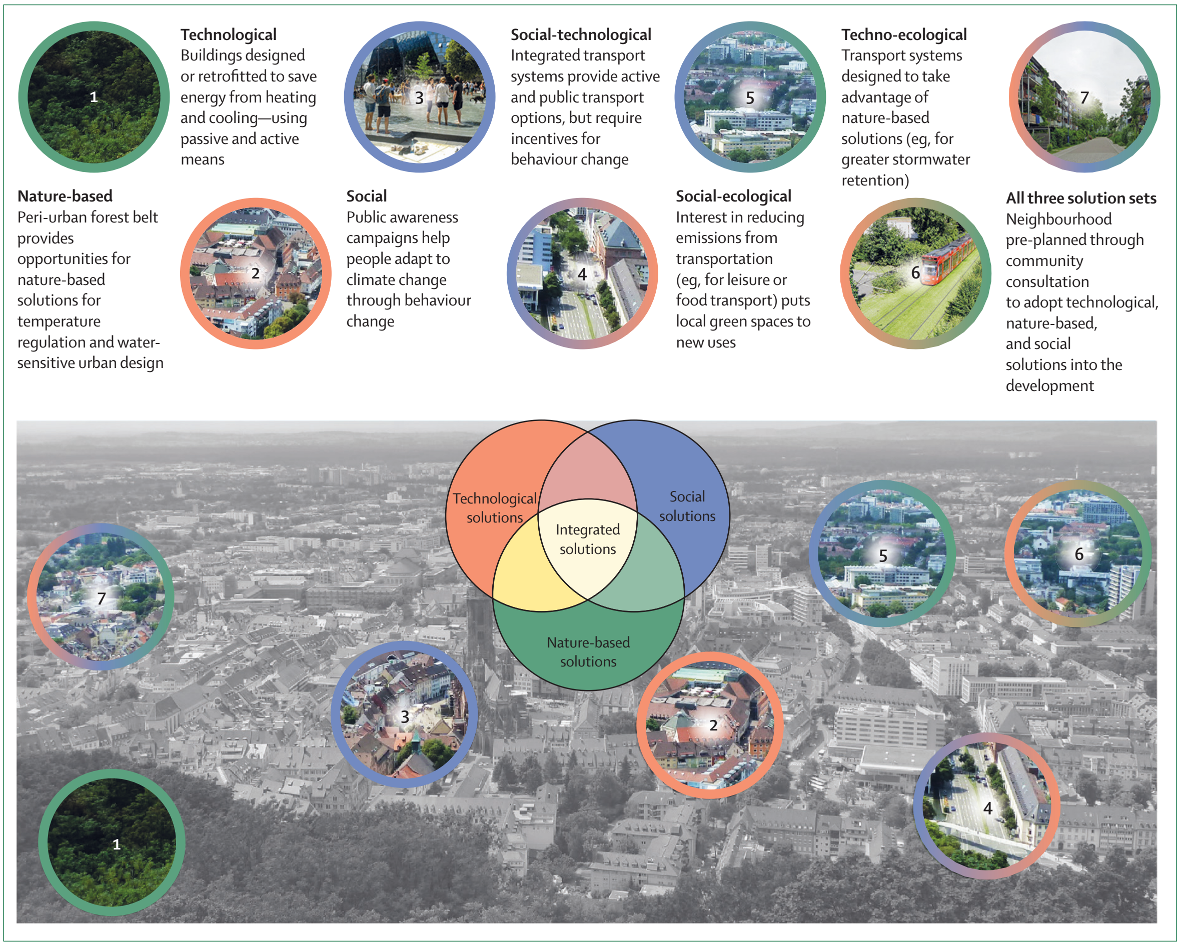

Figure 1: **Different circumstances across a city might require the integration of different solution sets**
In some locations one solution type might be the focus, whereas in other areas integration of different solutions will be crucial to delivering desired outcomes. This figure provides examples of how this diversity of solution integration and implementation can come together to create a multi-layered resilience for the city.

vegetation will provide cooler pathways for urban dwellers to travel during extreme heat events; however, a change in behaviour towards public or active transport might also require a social component to encourage communities to limit vehicle use and take advantage of these alternatives.[43] A change to more sustainable and affordable transport solutions, such as reducing car use and moving towards public transport or cycling, requires economic and psychological tools to encourage behaviour change (eg, incentives and disincentives).[44]

The Sustainable Development Goals (SDGs) aim to tackle several goals at once, including ending poverty (Goal 1), providing good health and wellbeing (Goal 3), building sustainable communities and cities (Goal 11), creating inclusive institutions at all levels (Goal 16), and more. The impacts of climate change on cities threaten all of these SDGs as well as those relating to biodiversity conservation. Taking climate action (Goal 13) is, therefore, essential to achieving sustainable cities because cities are already experiencing many of the impacts of climate change.[45] By adopting comprehensive suites of integrated solutions, multidimensional resilience can be developed to address the challenges (figure 1).

Challenges and enablers towards an integrated approach for adaptation

There is a large body of evidence of societal vulnerability to extreme heat, flood, and drought events, and immediate action is required to help with adaptation to, and mitigation of, the potential impacts of climate change in cities. Increasing rates of urbanisation will expose more urban dwellers to urban heat islands and extreme weather events, lead to urban expansion further into floodplains, and increase the damage risk faced by urban built infrastructure.[4] Even for cities that have the appropriate governance structures and processes, and financial capacity to respond to climate pressures, the convergence of urbanisation and fast-paced climate change might erode their ability to respond in an effective, equitable, and timely manner. The potential addition of 4 billion people to the poorest regions of the

Panel: Examples of potential challenges and enabling solutions

Potential challenge of competing priorities between current and future issues

Potential enabling solutions:

- Develop adaptive pathways that allow for current issues to be considered while planning for future change
- Maintain flexibility in planning to allow for changes in solutions over time
- Create solutions with many co-benefits that address current issues, but that do not create maladaptation to future change

Potential challenge of limited public space for implementing green strategies, and retrofitting infrastructure

Potential enabling solutions:

- Focus on improving the quality of existing green space
- Create incentives for changes to occur on private land
- Think creatively and strategically about new opportunities, for example, green walls, rooftop kitchen gardens, elevated greenways, and linear parks, designing multi-functional spaces

Potential challenge of limited resources (money and knowledge) at multiple scales

Potential enabling solutions:

- Develop opportunistic development of programmes that leverage existing projects
- Create social protection programmes that work on multiple sustainability focused objectives at once
- Use financial incentives (eg, payment for ecosystem service schemes) to help in instigating change by private citizens at scale

Potential challenge of dealing with uncertainty around timing and impact of climate change

Potential enabling solutions:

- Develop adaptation planning models that allow for flexible decision making over time
- Consider risk management that takes into account climate change impacts and timelines in prioritisation decisions
- Use adaptive designs via interventions that are easy to set up, dismantle, and rearrange
- Choose so-called no-regrets approaches to current options

globe will create increasing challenges towards ensuring equity and responsive adaptation.[46]

Many of the barriers are likely to be similar in systematically advantaged countries (sometimes referred to as the Global North) and systematically disadvantaged countries (sometimes referred to as the Global South), with normal operations siloed and opaque decision making reducing the capacity to develop integrated solutions.[47] However, cities are complex and varied, with different barriers, limitations, and opportunities (eg, resources, capital, and leadership) depending on their unique circumstances.[48] Previous work in urban sustainability emphasises that both systems thinking and complex adaptive solutions are needed,[49,50] and the need for such solutions is especially true of climate change-related impacts on cities.[51,52] Climate change will bring additional challenges to these already complex systems, in which transformations might have unintended trade-offs, especially in areas where the complexity is not well characterised.[49] Additionally, when rolling out any city-specific suite of solutions the sequence and timeline of the implementation of individual solutions needs to be considered. Although some solutions might have an immediate tangible effect, others could be effective only once enabling solutions are in place (panel).

Enabling integration through social–cultural change—Freiburg, Germany

Freiburg (population ~230 000 people, 153 km² area), located in the southwest of Germany, has a long history of citizen action, dating back to the 1970s. One of the main goals of citizen action was to reject nuclear power to focus on safer, energy-efficient sources. Although the campaign was originally focused on energy, the larger societal and cultural change that developed through this action has enabled Freiburg to overcome some of the major challenges to larger transformation and integration of adaptation solutions for climate change.[53] Many of the changes made were initiated at the local scale, but integration across jurisdictions has allowed for integration at multiple scales and large infrastructure projects.

At the city level, three main changes occurred. First, substantial gains in urban design were made to increase the accessibility of public transport. For example, as a techno-ecological solution, tram corridors were built with grassed, pervious surfaces as part of water-sensitive urban design and for stormwater drainage. As a social solution, public transport costs were subsidised to discourage car use.[54] Additionally, mixed-use zoning ensured that community needs were met locally (eg, schools, shops, services, and green spaces), thus reducing the need for private car ownership.[55] Second, design and maintenance of extensive green spaces for climate protection and human wellbeing was considered. Nature-based solutions, such as the active management of 600 hectares of parks and 5000 hectares of forest, supported community health and wellbeing while also reducing air temperatures by 2–3°C during heatwaves.[56] Finally, an effort was made to reduce carbon emissions and increase energy savings. As a socio-technical solution to encourage energy savings, a support programme to retrofit buildings (eg, putting in insulation) was instituted in Freiburg, reducing energy consumption by up to 38% per building across schools and offices.[53] Tax credits and subsidies from the federal government and regional utilities have encouraged the adoption of renewable energy.[54]

The integration of solutions was also implemented at the neighbourhood scale. An example of this the Vauban district, developed in the 1990s, which adopted a community co-governance structure to guide decision making, demonstrating inclusivity and a desire for alternative channels for decision making.[57] Integrated solutions within the single neighbourhood of Vauban were created through community co-development across multiple user groups to learn and design for various needs. For example, Vauban's buildings were designed with "Passivhaus" (translated as passive house) principles but were enabled through the integration of technological, nature-based, and social solutions.[55] The high-tech insulated buildings absorb solar heat during winter and allow for quick heat dissipation in the summer through passive ventilation. Linden trees (*Tilia* sp) shade buildings during the summer but allow for solar heating after leaf drop in autumn. A large educational campaign encouraged residential behaviour change, leading to about an 80% reduction in energy use.

Opportunistic integration to build adaptation pathways—Durban, South Africa

Durban, South Africa (population ~3·1 million people, 2292 km² area), is grappling with highly unequal social, economic, and environmental conditions. Durban is the largest container port on the African continent yet is South Africa's poorest large metropolitan area. Anticipation that climate change could undermine development efforts and exacerbate the plight of the city's most vulnerable residents has instigated a focus on adaptation. Key climate vulnerabilities for people in Durban include extreme heat, changing amount and distribution of rainfall, and sea-level rise—all of which affect ecosystem degradation and livelihood sustainability.[58]

In Durban, the main challenge associated with climate adaptation is competition for resources and political support with other development processes and projects in the municipality.[59] Adaptation, however, requires appropriate financial and technological support; thus, the proposed climate change adaptation projects needed to deliver as much benefit as possible, including to infrastructure and service delivery, tackling issues of inequality and developing economic opportunities for the community.[60]

Due to limited precedents, interest, leadership, institutional support, and resources, Durban's adaptation approach was necessarily phased and opportunistic.[61] The city relied on cultivating institutional champions who have deep sectoral knowledge, and who can then identify points of integration and overlapping spheres of influence and networks.[62] These policy champions were crucial in bringing climate change in as a key development issue and raising its profile.[58] For example, the municipality established a multi-stakeholder partnership to work on the development of biological infrastructure (combined ecological and technical solutions) to address increasing water security issues in the Umgeni River catchment. This type of integrated framework also helped in creating cross-sectoral coalitions (eg, between the municipal water, infrastructure, and energy departments) and strategic multi-stakeholder planning opportunities to allow for larger scale discourse of the adaptation agenda, and in creating a so-called no-regrets approach that took into account water, biodiversity, climate, and poverty challenges.[62]

Another enabler of integrated adaptation within Durban has been a move towards adaptive management that has allowed the city government to learn from successes and failures, and has generated a cycle of reflective practice to understand the complexity of adaptation actions.[63] Moving beyond siloed approaches and bringing in integrated approaches to develop multi-beneficial solutions can provide long-term sustainability gains that help overcome resource and political challenges.

Using big data to integrate information for adaptation planning—Singapore

Singapore (population ~5·4 million people, 724 km² area) is known as one of the most compact cities in the world.[64] This high pace of urbanisation has reduced forest extent in Singapore, but the concept of integrating green open spaces into buildings and urban infrastructure has earned Singapore the nickname of the Garden City. In the past decade, the emphasis has switched to becoming a City in Nature to strengthen biodiversity conservation and application of nature-based solutions.[65] Climate models project that temperatures will continue to increase in Singapore, with long-term mean temperatures of +1·4–4·6°C by 2100.[66] However, the compact urban design has also increased the urban heat island effect within the city, which can be in excess of 7°C between urban and rural areas in Singapore. Singapore's population, economy, and ecosystems are vulnerable to the negative effects of further temperature increases.[66]

Mitigating increasing temperatures from climate change and the urban heat island effect require integrated solutions for climate-sensitive design across Singapore's local environment. The challenge in Singapore is the competition for the limited space to make changes in a high-density city. Many solutions have been ecological and technological in nature, with urban design guidelines cognizant of building design technologies and the development of green roofs and walls, and Cooling Singapore, an interdisciplinary project between universities and the Government of Singapore, has resulted in the compilation of a strategy document specifically for Singapore's climate.[66] However, the new phase of research will use big data and spatial information platforms to develop an island-wide digital urban climate twin (DUCT) of Singapore by integrating relevant computational models (including environmental, land surface, industrial, traffic, building energy) as well as regional-scale and micro-scale climate models. The idea of such a DUCT is to develop a decision support system to help prioritise and select strategies across environmental, economic, and social facets.

In this sense, the technology to develop an integrated model of the city will help urban planners, engineers, and researchers weigh the benefits and costs of various planning scenarios, including integrated solution sets, to assess different cooling measures with the most benefits. These solutions might include innovative transportation

Figure 2: **Three examples of how integration can be enabled**
(A) Freiburg, Germany: citizen action can be harnessed to create a cultural change in values that enables broad integrated action (credit Daniel Schoenen). (B) Durban, South Africa: multi-institution connections can lead to opportunistic integrated measures (photo shows an example of integrated water and climate change adaptation, from Twitter[67]). (C) Singapore: the use of big data can allow for modelling of integrated actions to assist decision makers (credit Winston Chow).

systems, advanced building technologies, vegetation typologies, materials for buildings and pavements, and climate-sensitive urban design solutions across spatial scales. Developing this capability is crucial for the city planning agencies to create robust climate-informed policy making in the future.

The three case studies presented in this Viewpoint highlight that technological, nature-based, and social solutions can be combined as a suite that work in concert with each other to address many sustainability goals simultaneously, as well as produce outcomes that increase the resilience of the city to climate change across diverse socioeconomic contexts (figure 2). Developing, monitoring, and evaluating strategies to better allow for the understanding of their use in different contexts will be increasingly necessary for transferring and scaling up solutions.

Research directions and pathways forward

Integrating solutions that are context sensitive and locally grounded will be necessary to build urban resilience to climate change. Developing and implementing integrated solutions that embrace all three targets (ie, technically sound, nature-based, and socially equitable) will have many challenges and will require systematic research that aims to uncover the barriers to effective outcomes.

First, research on how to create enabling environments will allow for and support integrated solutions. The Freiburg case study shows a strong need for social supports across the community and for local governments to create neighbourhood-wide to city-wide integrated solutions. In Durban, identifying leaderships and creating multi-sectoral collaboration was necessary to take advantage of opportunistic integrated action. These examples highlight that adaptation and mitigation decisions should be developed with stakeholders through co-development processes to recognise the range of values within the community and to build collective agency and support for decisions.[68] Involving more people and co-producing knowledge can lead to a greater representation of experiences, knowledge, and interests that generate alternative ways of solving problems.[69] More research is required to understand how institutional enablers and barriers affect societal adaptation and behavioural change, and how cities can manage processes to encourage change at all levels of decision making.

Second, there is a need to understand how to integrate solutions in different contexts. Each individual solution will have different qualities and effects that might make it more or less effective when combined with other solutions. For example, the development of a bicycle pathway that is shaded with trees as well as created with permeable pavement can create a much cooler pathway than either of those two solutions alone. However, there might be trade-offs and feedbacks of one solution on the efficacy of other solutions. For example, nature-based solutions that involve water storage to reduce flood risk or to provide evaporative cooling, if not well managed, can provide breeding grounds for insect disease vectors. Thus, different alternatives for meeting the same targets will have to be considered, and flexibility to change the solutions across different urban contexts and climates will allow cities to take advantage of the strengths of varied solutions and to avoid competing goals and maladaptations.

Third, cities can invest in understanding how solutions can work together to improve liveability, sustainability, and equality. Much of the current research on urban sustainability comes from cities of the Global North, and there is a gap in understanding the social, environmental, and economic context in emerging urban regions of the Global South and how their ability to adapt to climate change can inform other cities globally. Many regions have been under-studied, particularly in the Global South, yet these regions have larger populations of vulnerable urban groups with less access to resources, and are thus disproportionately affected by climate extremes.[45,70] Crucially, informal urban settlements in many developing countries have little access to technological solutions and might depend primarily on nature-based solutions to adapt to climate challenges due to their relatively low cost and broad accessibility.[71] Climate change adaptation and mitigation measures might exacerbate socioeconomic inequalities across populations within a city, across cities globally, or even inter-generationally. Alternatively, actions taken now can have compounded benefits for future generations.

Lastly, researchers can work with decision makers of cities in a coordinated approach to take these localised solutions and find ways to connect, amplify, transfer, and scale up solutions and innovations at a sustained pace that can effectively respond to climate change in cities. This approach might mean that cities will need to monitor and evaluate their own solution sets while also collaborating and translating learnings across cities. Collaboration and cooperation across cities will need to transcend administrative boundaries, sectoral responsibilities, and knowledge groups, and organisations such as C40 and ICLEI are creating networks to create knowledge bridges. Some learnings can be scaled up regionally or transferred to cities with similar climate, landscape types, and populations; however, many proposed solutions will not be immediately suitable for deployment in a particular city and will require further development and context-sensitive translation.[72] Coordinated actions might also require different coalitions and governance structures to develop integrated ways of problem solving and future visioning or foresighting.[39]

Conclusions

Integrating solutions for adapting to climate change offers opportunities and great potential for long-term sustainable change. However, there are challenges to creating and implementing integrated solutions, including competing priorities, lack of resources, and planning under uncertainty. The three case studies show that there are enablers, such as citizen action, multi-institutional opportunism, and big-data scenario modelling, which can help overcome these challenges, but more research is needed. A better understanding for how to create enabling environments, how to integrate solutions in different contexts, how solutions can be complementary, and how to transfer and scale up solutions are all important next steps for embedding integrated solutions into the urban adaptation decisions of cities globally.

Contributors

BBL and AO conceived the idea for this Viewpoint. BBL led the writing and development of the Viewpoint. AO led the development of figures with support from TM. All authors contributed to the literature review, writing, revising, and editing of the Viewpoint.

Declaration of interests

We declare no competing interests.

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