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Nature-based approaches to managing climate change impacts in cities

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Managing and adapting to climate change in urban areas will become increasingly important as urban populations grow, especially because unique features of cities amplify climate change impacts. High impervious cover exacerbates impacts of climate warming through urban heat island effects and of heavy rainfall by magnifying runoff and flooding. Concentration of human settlements along rivers and coastal zones increases exposure of people and infrastructure to climate change hazards, often disproportionately affecting those who are least prepared. Nature-based strategies (NBS), which use living organisms, soils and sediments, and/or landscape features to reduce climate change hazards, hold promise as being more flexible, multi-functional and adaptable to an uncertain and non-stationary climate future than traditional approaches. Nevertheless, future research should address the effectiveness of NBS for reducing climate change impacts and whether they can be implemented at scales appropriate to climate change hazards and impacts. Further, there is a need for accurate and comprehensive cost–benefit analyses that consider disservices and co-benefits, relative to grey alternatives, and how costs and benefits are distributed across different communities. NBS are most likely to be effective and fair when they match the scale of the challenge, are implemented with input from diverse voices and are appropriate to specific social, cultural, ecological and technological contexts.

This article is part of the theme issue ‘Climate change and ecosystems: threats, opportunities and solutions’.

1. Introduction

Devising strategies to manage and adapt[1] to the impacts of climate change in urban areas will become increasingly important as the global population becomes more and more concentrated in cities and climate continues to change in ways that have potentially severe impacts on urban populations and infrastructure. Some urban climate change hazards (physical manifestations of climate change that have detrimental consequences for human well-being) will be especially challenging to manage (i.e. to reduce) because urban environments interact with and influence climate in ways that can amplify (worsen) those hazards. This leaves urban residents with no choice but to adapt to those hazards, reducing exposure to hazards or their harmful effects, or to retreat. On the other hand, cities offer opportunities for managing and adapting to climate change hazards because most services and institutions are located within cities.

There is increasing interest among city practitioners in using ‘nature-based’ strategies [2], a broad suite of actions aimed at promoting human well-being in cities using approaches that restore aspects of ‘natural’ (non-urban) ecosystem structure and/or function. These strategies are seen as more flexible, multi-functional and adaptable to an uncertain climate future than traditional, more rigid, approaches [3–5]. Herein, we review the potential for nature-based strategies (NBS) to reduce climate change hazards in cities. NBS include parks and open space; intentional plantings; construction of structures that

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restore natural hydrologic function such as stormwater ponds, bioswales, green roofs, riparian zones; and restoration and protection of natural protective habitats along coastlines [5]. We begin by reviewing the primary climate change hazards faced by urban residents, highlighting how cities can amplify many of those hazards (§2) and the impacts of climate change hazards on social, ecological and technical (SET) components of cities (§3). We then review opportunities to use NBS to reduce exposure to climate change hazards (§4) and manage and adapt to the SET impacts of those hazards (§5). We conclude by identifying research priorities (§6).

2. Exposure to and amplification of climate change hazards in cities

Cities often are at great risk from climate change because human settlements are concentrated in areas that increase the vulnerability of people and infrastructure to climate change hazards [6]. Furthermore, cities have unique features, such as high impervious and low pervious cover, that amplify some aspects of climate change. Thus, several aspects of climate change are expected to be acutely felt by urban populations, including sea-level rise, higher mean and night-time temperatures, reduced snowpack or rainfall leading to water scarcity, and increased frequency and magnitude of extreme events like heavy precipitation, heat waves, coastal storms, river flooding and drought (table 1). Indeed, extreme events are the aspect of climate change that will have the most direct and obvious impact on the greatest number people in their lifetimes.

(a) Sea-level rise and coastal storms

The rate of sea-level rise is increasing, with projections of 0.3–1.3 m by 2100 [8]. Globally, human populations and most major cities are concentrated in low-elevation coastal zones [9], increasing the exposure of people and infrastructure to inundation, storm surge, flooding, erosion and salt-water intrusion. For example, populations in nine Asian mega-deltas are greatest in areas less than 10 m above sea level, and many of these populations are growing rapidly [10,11]. In some sensitive, low-lying areas, such as much of South Florida (USA), groundwater levels are carefully managed to prevent intrusion of sea water into the water supply for greater than 5 million people. However, higher groundwater elevation reduces water storage capacity of surface soils, and may amplify overland flooding [12] and ultimately necessitate retreat from the coast (table 1).

Coastal cities also experience storms that exert impacts through flooding and sea surge, erosion and wind, and which are projected to increase in frequency and magnitude [13]. Sea surge can dramatically amplify coastal flood risk. In the case of superstorm Sandy (New York City, USA) in 2012, sea surges coincided with high tides, flooding subways and coastal infrastructure, and inundating an area equivalent to that projected to flood under a 2080 scenario of rapid ice-melt [14]. Erosion caused by the storm also undermined infrastructure along much of the local coastline.

High winds from tropical cyclones can prove devastating to ecological and technological infrastructure on coasts, although wind speeds decline rapidly once making landfall. The coastal cities of East Asia, particularly those in the Pearl River Delta, Tokyo and Manila, are most at risk from this type of extreme event [15]. Inland, windthrow and infrastructure damage can result from other types of storms. Regardless of storm type, high winds also produce health risks because of entrainment of air pollutants, including disease organisms [16]; this risk is amplified in cities because they often have elevated concentrations of air pollutants, including particulate matter, ozone and toxins.

(b) Extreme heat

Global mean temperature has increased 0.8°C since 1880 [17] and will continue to rise. Warming is exacerbated in cities by the urban heat island (UHI) effect, whereby cities are warmer on average than surrounding areas [18]. For example, US cities are warming 1.5 times faster than rural areas [19]. A number of factors combine to cause UHI effects [20]: lack of vegetation and associated cooling effects of evapotranspiration, high capacity for heat storage in building materials, high aerodynamic resistance to heat dissipation and generation of waste heat from energy use by buildings and vehicles.

Hotter conditions drive impacts on cities through several mechanisms (table 1). Exceedance of thermal tolerances constrains activity of humans and other organisms, especially at low latitudes. Prolonged human exposure is exacerbated by the UHI, rising night-time minimum temperatures and longer warm seasons. The energy system is stressed by increased demand for cooling. Higher temperatures also exacerbate drought stress and worsen air pollution and episodes of air stagnation resulting from thermal inversions. The impacts of heat waves thus will be intensified in cities [21].

Heat waves will be especially likely to cause heat stress in hot and humid regions [20,22], since heat stress is a function of both temperature and humidity (along with physiological and behaviour factors) [23]. In a global analysis of heat waves and human mortality, temperatures of only 20°C were lethal (i.e. were associated with excess mortality) when relative humidity was high (80%), whereas the lethal temperature increased to 30°C at low relative humidity (20%) [24]. Based on these empirical relationships, Jakarta, Indonesia, is therefore predicted to experience anywhere from 117 to 365 d yr^{-1} of lethal temperature–humidity combinations by 2100 (for a low- versus high-emissions scenario, respectively), compared with 9–50 d yr^{-1} in New York City, USA [24].

(c) Water security, inland storms and pluvial flooding

Compared to temperature change, hydrologic impacts of climate change will be orders of magnitude more spatially and temporally variable. Because most cities rely on regional or distant watersheds for their water supply, or on groundwater sources that are replenished slowly, the impacts of climate change on hydrology over broad areas are important for urban water security. Changes in the total amount, intensity and seasonality of precipitation all have potential to influence urban areas. These changes will vary in space, with some regions seeing greater precipitation and some seeing less [8]. Cities amplify drought through increased water demand for maintenance of vegetation or cooling.

Of all natural disasters, river flooding exposes the most people (379 million) [15] to climate-related hazards. Much of urban infrastructure is located along rivers and even in riverbeds, where it is vulnerable to inundation and riverbank

Table 1. Climate change hazards that threaten cities. Included are the mechanisms by which these hazards impact social (S), ecological (E) and technical (E) aspects of cities, nature-based approaches to managing and adapting to these impacts, and, for comparison, alternative strategies that are not nature-based solutions (e.g. 'grey' infrastructure).

climate change hazards	mechanisms of impact	impacts (S, E, T)	nature-based adaptation and management strategies	alternative 'grey' strategies
sea-level rise	salt-water intrusion	S, E	none (retreat)	alternative water supplies desalinization
	tidal inundation	S, T	none (retreat)	bulkheads sea gates dikes pumps
coastal storms	sea surge: flooding	S, E, T	mangroves, wetlands, dunes, reefs	sea walls sea gates dikes pumps
	coastal erosion	S, E, T	mangroves, wetlands, dunes, reefs	sea walls bank stabilization, armouring
wind storms (coastal or inland)	high winds: blow-down	E, T	wind-resistant plantings	wind-resistant, buried infrastructure
	wind entrainment of particles	S	plants to filter air-borne pollutants	avoidance
inland storms—riverine flooding	overbank flooding: inundation	S, E, T	wetlands ponds reservoirs floodplain widening	levees
	erosion, bank failure	E, T	wetlands channel restoration tree planting floodplain widening	bank stabilization, armouring

(Continued.)

Table 1. (*Continued.*)

climate change hazards	mechanisms of impact	impacts (S, E, T)	nature-based adaptation and management strategies	alternative 'grey' strategies
inland storms—pluvial flooding	damage from high flows	S, T	tree canopy cover to promote interception and slow flows green infrastructure[a] to slow flows and promote infiltration, especially in 'headwaters'	channelization storm drainage capacity pervious pavement
	inundation of low-lying areas	S, T	wetland restoration, retention basins	pumps pervious pavement
	transport of pollutants from land to stormwater system	S, E	green infrastructure[a] to slow flows and promote infiltration	water treatment street narrowing pervious pavement
	combined sewer overflows	S, E, T	green infrastructure[a] to slow flows and promote infiltration constructed treatment wetlands	sanitary and storm sewer separation storage tanks
higher overall temperature	thermal intolerance (reduced recruitment, increased mortality), phenological shifts	E	managed relocation	
	exacerbated urban heat island	S, E, T	tree canopy cover parks and open space green roofs	air conditioning misting stations swimming pools light-coloured building materials heat-resistant building materials
	drought stress	E	plantings for drought tolerance	irrigation
higher night-time temperature	exacerbated urban heat island, prolonged human exposure	S, E	tree canopy cover parks and open space green roofs	air conditioning swimming pools

(*Continued.*)

Table 1. (*Continued.*)

climate change hazards	mechanisms of impact	impacts (S, E, T)	nature-based adaptation and management strategies	alternative ‘grey’ strategies
heat waves	increased human exposure	S	tree canopy cover parks and open space green roofs	air conditioning misting stations swimming pools light-coloured building materials
	increased demand for cooling	T	tree canopy cover parks and open space green roofs	air conditioning misting stations swimming pools light-coloured building materials heat-resistant building materials
	thermal inversions: trapped air pollutants	S, E	tree canopy cover[b]	remaining inside and reducing activity building to promote advection
extreme cold	increased demand for heating; increased human exposure	S, T	wind breaks	heating
drought	water use restrictions	S, E	green infrastructure[a] to slow flows and promote infiltration landscaping for drought tolerance runoff, grey water capture and reuse rainwater capture	replacing landscaping with hardscaping
	increased water scarcity	S, E	green infrastructure[a] to promote infiltration and groundwater recharge landscaping for drought tolerance runoff, grey water capture and reuse rainwater capture protection of upstream watersheds	groundwater pumping water transfer systems
	water conflict	S, T	none	water transfer systems graded water pricing treaties
	reduced water quality	S	green infrastructure[a] to promote nutrient uptake restored wetlands	water treatment

[a] Stormwater ponds, raingardens, bioswales, parks and open space, green roofs and similar structures.

[b] The net effect of increased tree canopy cover on air pollution is unclear, as trees both remove and produce and trap pollutants [7].

erosion. Cities have traditionally sought to armour and strengthen their banks using built infrastructure rather than rely upon natural floodplains (table 1). This dependence upon levees, channel straightening and hardening can produce a false sense of security, especially given the changing probabilities of flooding [25,26].

High impervious cover in cities exacerbates the impacts of heavy rainfall and magnifies urban runoff and flooding. Roads, parking lots, buildings and other impervious surfaces prevent infiltration. Combined with dense drainage networks, low infiltration causes higher volume and more rapid runoff [27–29]. High impervious cover also promotes pluvial flooding, flooding that occurs when precipitation rates exceed the capacity of stormwater systems or infiltration [30]. Such flooding can occur far from coasts or rivers as a result of brief, intense rainstorms, and will become more common as the frequency and magnitude of extreme rainfall increase [8]. Pluvial flooding can damage infrastructure directly through the force of flowing water, and is often unpredictable; for example, US Federal Emergency Management Administration (FEMA) flood maps usually do not apply to pluvial flooding [30]. In general, low places in the urban landscape are most at risk and often inhabited by people with the lowest capacity to adapt or respond.

(d) Other climate-change-related hazards

In addition to temperature- and water-related hazards, cities are potentially exposed to extreme events and disturbances such as fires, tornados, hurricanes, landslides and seismic events, some of which may be exacerbated by climate change. Human decisions and settlement locations strongly influence the exposure of urban residents to these hazards; for example, fires that once levelled cities around the turn of the twentieth century no longer pose a threat, but fires at the urban–wildland interface are on the rise [31]. As people are increasingly settling at this interface [32], future increases in fire resulting from climate change [33] will likely increase human mortality. Even when fire does not directly threaten urban lives and settlements, wildfires can expose downwind urban residents to severe air pollution, worsening heat-related mortality, as happened in Moscow during the Russian heat wave of 2010 [34].

3. Climate change impacts on social–ecological–technical components in cities

(a) Social impacts

In cities, extreme temperatures aggravated by UHI effects will cause a host of heat-stress-related physical health impacts [35], including heat stroke mortality and morbidity, dehydration and related illness, and heat exhaustion [36]. The most vulnerable include the elderly, young and socially isolated, those who lack air conditioning, outdoor workers and those experiencing homelessness [35–37]. Within cities, the poor may be more vulnerable to heat exposure because they often lack air conditioning and live in neighbourhoods with less vegetative cooling capacity [38,39]. Heat exposure will also reduce the capacity for physical activity, reducing worker productivity and exercise activities [36].

Heavy rains and associated pluvial flooding also can affect human health. Urban runoff entrains and transports heavy metals, nutrients, salts and pathogenic bacteria from the landscape to stormwater systems [40,41], resulting in pulses of high pollution downstream and creating episodic risks to public health and aquatic ecosystem health. Combined sewer overflows (CSOs) occur when runoff from heavy rains overwhelms sewers carrying both stormwater runoff and human waste, leading to releases of untreated sewage into surface waters to prevent sewer backups [42].

Climate change can cause human mortality, injury and displacement directly, by posing immediate hazards, and can also drive displacement by influencing economic, political, demographic and social drivers of migration [43,44], with the greatest impacts in low- to middle-income countries [45]. Exposure of many urban residents to hazards associated with sea-level rise, storms and river flooding may mean the damage or loss of homes, safety concerns from erosion undermining buildings or roads, and contamination of drinking water supplies. The poor, such as those in informal settlements, are at greatest risk because they lack adequate housing and other infrastructure, clean water, and access to healthcare and emergency services [46]. Extreme heat will make parts of the world without significant capacity for adaptation uninhabitable. Even holding average global warming to 1.5°C since pre-industrial times, 40% of mega-cities, concentrated in Africa and Asia, will experience periods of deadly heat indices each year [47]. Warming of 4°C will translate into periods of deadly heat indices in nearly 80% of the world's mega-cities.

Exposure to climate-change-related hazards will have mental as well as physical health impacts, including in cities. Weather-related disasters have been related to post-traumatic stress disorder, depression and anxiety [48]. Extreme heat has been linked to aggression, criminal behaviour, suicides, mood disorders and dementia. Disruptions to livelihoods and health caused by climate-change-related damage of infrastructure and forced migration will disrupt social systems and social ties, reducing adaptive capacity of climate change migrants [48,49].

(b) Ecological impacts

Ecological systems in cities are particularly vulnerable to climate change because of interactive effects with disturbances, pests and pathogens, and stressors such as road deicers and soil compaction. In addition, rapid urban expansion in many parts of the world likely will alter regional biodiversity [50].

Correlations between climate factors and plant diversity suggest that urban biodiversity will be sensitive to climate change. For example, across cities, those with higher maximum temperatures had lower plant species richness of both cultivated and spontaneously occurring plants in residential yards [51]. On the other hand, richness of spontaneous species increased where winters were relatively mild, a pattern also seen for urban trees across North America [52]. Thus, climate change may reduce plant species richness in regions that are already hot, but increase it in colder regions.

Because of UHI effects, limited plant rooting volumes, compacted soils and contamination by pollutants such as heavy metals, pesticides, herbicides and salts [53–56], climate change likely will worsen heat- and drought-related stress on urban ecological communities [57], particularly where impervious cover and local temperatures are highest [58–60]. Under these stresses, species are likely to be more vulnerable to pests and pathogens, whose populations and ranges may expand with climate change [61,62].

Urban tree cover may be reduced by climate change because many species of trees currently being planted in cities will not be suited to future climates [63,64]. In addition, cities are at risk from accidental introductions of novel pests and pathogens by the nursery trade [62], and low diversity of urban forests may promote establishment and spread of these pests and pathogens [65]. Urban trees are susceptible to damage and mortality from windthrow associated with more intense storms, as the root systems of urban trees often are inadequate to support trees during high winds [66]. This is because urban soils often are compacted, waterlogged, drought-stressed or contain fills, and because trenching, construction or mowing can damage root systems.

In urban lakes and ponds, higher water temperature combined with high nutrient loads will promote blooms of algae and harmful cyanobacteria [67,68] and extend the period of stratification [69]. Blooms combined with reduced exchange of deep waters with oxygenated surface waters can result in hypoxic events, which kill fish and benthic biota and stimulate anaerobic biogeochemical processes that release sediment nutrients into the water column, further contributing to urban lake eutrophication [69]. More thermally stable and warmer surface waters, among other factors, will promote harmful cyanobacteria [67], increasing exposure of urban residents and pets to cyanobacterial toxins [70].

Most streams in urban areas are drastically altered through channelization, burial and impoundment [71], which reduces their capacity to withstand climate-related impacts such as rising water temperature [72], increased peak flow associated with extreme events [29] and increased nutrient and pollutant loading from storms and CSOs. Both urbanization and climate change interact to adversely affect stream fish populations and communities, according to models manipulating the two drivers individually and in combination [73].

(c) Technical impacts

Technical or infrastructure systems are designed and managed to deliver specific services or protect urban populations. Services provided include electrical power, water delivery, mobility (i.e. transportation) and waste management; stormwater infrastructure, seawalls and levees, and climate-controlled buildings (for shelter) provide protection for urban populations [74,75]. Climate change will have strong impacts on infrastructure because of its location, age, design and exceedance of design limits.

Infrastructure is more dense and is co-located in cities, amplifying technical impacts of climate change hazards such as storms, as a storm of a given extent and intensity will cause more damage in urban than in rural areas. Furthermore, urban infrastructure such as power lines, sewer pipes and water delivery networks often occurs along public rights of way like roads or streams, which may be vulnerable to flooding. Thus, the co-location of multiple infrastructure systems can result in simultaneous failures. Waste removal infrastructure in some cities is combined with stormwater conveyance, with both water streams merging at wastewater treatment plants where pollutants are removed. During flooding, however, CSOs occur. Thus, there are benefits of co-location but also potentially severe consequence when systems fail or their capacity is exceeded.

Infrastructure built to withstand historical climate is beginning to fail as extreme events become more common, and building for the past will be inadequate in a non-stationary world. Many systems are not robust to extreme events that are happening with ever-greater frequency, not just because of old age and deteriorating condition [76], but because they are built to design standards based on past probabilities (e.g. 1% is a common standard) [77]. This practice is inadequate in a non-stationary, uncertain world where the future probability of an event cannot be predicted from knowledge of the past. Recent efforts to employ non-stationary flood-frequency analyses [78] show promise for rethinking infrastructure design.

4. Opportunities for reducing exposure to climate change hazards with nature-based strategies

NBS make use of living organisms, soils and sediments, and/or landscape features to reduce climate change hazards or the amplifying effects of urban features on those hazards. Such strategies can provide alternative or complementary approaches to technical strategies and delay the need for human relocation, buying time to accelerate climate change mitigation (table 1) [3,79,80]. Diverse NBS, also referred to as green infrastructure or low-impact development [81], range from highly engineered structural stormwater control measures to parks and open space, building materials and designs incorporating natural elements, conservation and restoration of natural ecosystems particularly on coastlines, and intentional plantings (table 1) [5,80]. (Pauleit *et al*. [7] provide a useful lexicon for nature-based solutions, ecosystem-based adaptation, ecosystem services and urban green infrastructure.)

(a) Sea-level rise and coastal storms

NBS can reduce the growing risks of coastal flooding and erosion from higher storm surges accompanying sea-level rise. Conserving and restoring near shore habitats such as barrier islands, coral and oyster reefs, and kelp and seagrass beds, and coastal habitats such as dunes, mangrove forests and saltmarshes can reduce erosion and protect human settlements [82]. These habitats dissipate wave energy, attenuate wave height, reduce storm surge, and trap and stabilize soils and sediments [5,83], and are thus more resistant (i.e. they sustain less damage) and more resilient (i.e. they can potentially self-recover) to damaging effects of storms than grey infrastructure, such as bulkheads and sea walls [79,83,84].

No nature-based strategy can entirely prevent the gradual march of seas inland because of sea-level rise. Costly engineered structures such as sea gates, dikes and pumps, along with development of alternative water supplies, can delay the need for human resettlement. Yet, managing inundation and salinization of drinking and irrigation water supplies ultimately will necessitate retreat from coastal areas and relocation of coastal residents [85]. Nevertheless, NBS such as mangrove forests and salt marshes in some instances may establish shoreward through sediment accretion to keep pace with sea-level rise [83], if there is adequate space between any coastal development and the waterline.

(b) Extreme heat

Urban green space, in the form of parks and open space, green roofs and tree canopy, has received a great deal of attention regarding its potential to reduce the UHI and provide relief from climate-change-induced heat waves [19,86,87]. A meta-analysis of the cooling effects of urban green space in cities throughout the world found that parks were 1°C cooler on average than non-park areas, presumably because of high evaporative cooling and low heat storage, and these cooling effects extended well beyond the park boundaries. Local-scale cooling was the only nature-based benefit rated as 'high' among ecosystem services (including climate regulation, air quality regulation and carbon sequestration) assessed for the Barcelona, Spain metropolitan area [88]. On hot summer days in Phoenix (Arizona, USA), vegetated surfaces can be as much as a 25°C cooler than bare surfaces [38]. Studies of the cooling effects of green roofs in cities from tropical, subtropical and temperate regions found inconsistent temperature differences between green and nearby non-vegetated roofs [86]. Nevertheless, a modelling study of climate change in US cities found that 100% deployment of green roofs offset projected climate warming [89], although reflective roofs (technical strategy) were more effective at cooling than green roofs. Trees provide shade and evaporative cooling and are generally cooler than nearby areas without trees [86]. Therefore, increasing tree canopy in cities is projected to offset some climate warming and UHI effects [90]. However, in one city, nonlinear effects of tree canopy were found, whereby increasing the canopy cover did not yield significant cooling effects until relatively high canopy cover was reached [91]. Furthermore, cooling effects of tree canopy were lower at night and when impervious cover was higher.

(c) Inland storms, pluvial flooding and droughts

NBS such as green roofs, stormwater ponds, bioswales, raingardens and retention basins can promote infiltration and groundwater recharge and/or evapotranspiration, thereby reducing runoff volumes and flow rates during heavy rain storms [92,93]. If placed strategically in the landscape, i.e. dispersed throughout the landscape and placed adjacent to roads, such strategies can decrease risks of pluvial flooding [94] and the damaging effects of high-velocity runoff. For example, in simulations of a Chicago (IL, USA) watershed, having 10% of the landscape area in green infrastructure minimized flood risk associated with moderate storms. However, increasing the storm intensity to that expected under climate change (today's 1% probability), required increasing areal extent of green infrastructure by a factor of two or more to manage flooding [94]. Indeed, many nature-based interventions in stormwater systems are implemented at too small a scale to have any effect on large-scale, catastrophic events [95]. Thus, significant land area of stormwater green infrastructure will be needed to manage increased flood risk in regions predicted to experience more severe storms.

Many cities have been focused on increasing urban tree canopy cover, in part to reduce stormwater runoff volumes [96,97]. By intercepting rainfall, which is stored in the canopy and eventually evaporated [98], trees may reduce stormwater runoff volumes and delay peak flows during low-intensity rainstorms [98]. Transpiration by trees can potentially reduce runoff by providing greater soil volume for water storage [98].

Many cities are expanding use of green stormwater infrastructure to reduce runoff volumes during heavy rain events, reduce the risk of CSOs and potentially improve water quality [99–101]. Green infrastructure provides some capacity for pollutant removal from stormwater [101] and for receiving and treating CSOs (e.g. constructed wetlands) [102]. Stormwater green infrastructure traps particulate nutrients and promotes sorption, biotic uptake or gaseous losses of soluble nutrients [5,103,104]. Thus, increasing green infrastructure in the watershed may reduce stormwater export of nutrients to streams [93,105]. On the other hand, increasing tree canopy cover near streets contributes litter-derived nutrients to stormwater [106,107] and green roofs show inconsistent water quality benefits [108].

5. Managing and adapting to social, ecological and technical impacts of climate change using nature-based strategies

Besides reducing climate change hazards and the amplification of these hazards in cities to minimize climate change impacts, nature-based approaches can help cities manage and adapt to the SET impacts of climate change when they occur (table 1). The occurrence of disasters may represent opportunities for city governments to go beyond impact and effect real change or adapt by 'building back better' [109,110]—a social response that may incorporate NBS. In rapidly urbanizing areas, such as in sub-Saharan Africa and many parts of Asia, cities have the opportunity to address climate change as they develop, implementing NBS in the most effective combinations with grey infrastructure and in ways that maximize locally valued co-benefits [111,112].

(a) Managing social impacts using nature-based strategies

Many NBS to manage and adapt to climate change (table 1) have potential social co-benefits. For example, access and exposure to green space in cities improves aspects of mental and physical health [5,113,114]. Urban green space also has been linked to social benefits such as reduced violence and crime, although conflicting results indicate a need to understand mechanisms underlying potential links as well as for standardized approaches to quantifying them [113,115]. Whether NBS to addressing climate change in cities will have additional social benefits by countering the detrimental social effects of climate change, including impaired mental health, reduced social cohesion and increased violence, remains unknown. What is certain, however, is that the success of NBS is in large part dependent on public acceptance [116].

(b) Managing ecological impacts using nature-based strategies

Myriad opportunities exist to manage urban ecosystems to facilitate transitions to species more suited to a changing climate [64]. For example, forest managers in Chicago, IL, USA, identified a number of management actions to reduce urban forest vulnerability to climate change [64]. Increasing the

Table 2. Research priorities related to implementing NBS for addressing climate change hazards and their impacts.

Ten priority research questions
Effectiveness
1. What kinds, amounts and arrangements of nature-based strategies mitigate different climate-change-related hazards?
2. How transferable are nature-based strategies among cities?
3. Are there nonlinearities (e.g. thresholds or limits) that influence the effectiveness of nature-based strategies for mitigating particular climate-change-related hazards?
4. Can the amounts and arrangements of green infrastructure be designed to mitigate multiple hazards simultaneously?
5. Under what conditions will climate change hazards overcome the capacity for nature-based solutions to reduce SET impacts in cities?
6. What approaches are most effective for designing for future rather than past climate conditions?
Costs and benefits
7. What are the costs (including disservices) and benefits (including co-benefits) of nature-based strategies relative to grey alternatives, in different social, environmental and technical contexts?
Equity and environmental justice
8. How can the costs and benefits of nature-based solutions be distributed equitably across different communities within cities?
9. How can cities avoid 'green gentrification' and other unintended outcomes of implementing nature-based strategies?
10. How can the implementation of nature-based strategies accelerate improvement of living conditions in the world's poorest, but fastest-growing, cities?

diversity of plantings in developed areas and installing drainage systems to reduce flooding could reduce vulnerability of urban forests to extreme events. Planting more drought-, flood- or heat-adapted species and more pest- and pathogen-resistant varieties could facilitate the transition to species better suited to future climate.

In theory, many of the NBS for reducing climate change hazards have co-benefits for biodiversity in a changing environment, by providing habitat reserves and corridors for species migration in the face of climate change. However, NBS for reducing climate change hazards are not automatically optimal for conserving biodiversity and facilitating ecological adaptation to climate change. A number of factors might impede efforts to achieve biodiversity goals [117–120]. These factors include the challenges of coordinating management of distributed (often private) small patches of green space to create habitat patches or corridors at a scale appropriate to promote species of interest; goals for green space that conflict with biodiversity goals; management practices that might be outright detrimental to achieving biodiversity goals (e.g. mowing, trimming, use of herbicides and pesticides, planting of ornamentals); and misunderstanding of biodiversity benefits and negative perceptions of urban green space managed for biodiversity that might generate dissatisfaction among urban residents. Thus, enhanced ecological adaptation to climate change impacts will not occur as an inevitable outcome of implementing NBS to reduce climate change hazards, but potentially could be helpful if pursued with intent and accompanied by education efforts [118].

(c) Managing technical impacts using nature-based strategies

The use of nature to modify the built infrastructure of a city may seem antithetical to managing technical impacts in a city, but in fact many engineers are seeing the value of incorporating a systems view and redefining risk in the context of a non-stationary world [42,74]. Designs that move away from emphasis solely on the probability of an event to also consider its consequences allow for more flexible, adaptable infrastructure that is safe-to-fail, not just fail-safe [77]. For example, the use of protective wetlands along coasts [82] may reduce the hazard of erosion or wave damage from storm surges to coastal infrastructure. NBS can help to counter technical impacts when used alone or in combination with technical strategies (also known as hybrid strategies) along an eco-technical spectrum [121] or green–grey gradient [122,123].

6. Research priorities

Below, we articulate three priority research areas related to using NBS to manage and adapt to climate change in cities, articulating specific research questions in table 2. We propose that in planning for investment in NBS to address climate change hazards, a city needs to consider the effectiveness of NBS to reduce climate change hazards and their impacts, both now and in the future; the costs and benefits of implementing nature-based versus alternative strategies; and equity and environmental justice issues related to the distribution of costs and benefits across different cities globally and across communities within cities. Answers will depend on the particular social, environmental and technical context of each city; in other words, there is no *a priori* reason to expect 'one size fits all' solutions to cities' climate change hazards.

(a) How effective are nature-based strategies at reducing the impacts of climate change hazards?

Research should address the degree to which NBS can be implemented at scales that match the scale of hazards and impacts caused by climate change [116] (table 2). Such scaling questions need to be addressed in the contexts of individual cities: their local biome, climate and hydrogeology (e.g. sources of surface and groundwater); the magnitude and types of anticipated climate change hazards (e.g. droughts, extreme rainfall, sea-level rise); their specific SET characteristics (e.g. spatial segregation of risks, the age, type and distribution of green and grey infrastructure, and the social barriers to implementation of NBS); and opportunities to combine green with grey infrastructure. An important question is how NBS scale with implementation area, and how their effectiveness alone or in combination with grey infrastructure depends on their physical position in the landscape [84,93,94,116]. For example, a study of green roofs in Beijing, China, found that the reduction in UHI scaled linearly with green roof area: while 100% green roof coverage resulted in significant city-wide cooling (1.5°C), 10% green roof coverage led to only 0.1–0.2°C cooling [124]. On the other hand, a study in Madison (Wisconsin, USA) found that temperature was related to tree canopy cover in nonlinear ways that depended on impervious cover, spatial scale and time of day (daytime versus night-time) [91]. Given that space is limited in most cities, or its use for public good is complicated by private ownership, implementing NBS at sufficient scales and in appropriate configurations to allow meaningful adaptation may not be feasible given projected climate change impacts. Furthermore, many NBS require significant development time to reach maximum efficacy [125], or efficacy may increase and then decrease over time, owing to growth of plants, changes in substrate (e.g. soils and sediments) and deposition of litter or particulate matter. Thus, scaling in time as well as in space must be considered to fully understand the benefit–cost ratio of NBS.

(b) What are the costs and benefits of nature-based strategies relative to alternatives?

There is a need to accurately and comprehensively analyse costs and benefits, including disservices and co-benefits, of NBS relative to grey (or non-nature-based) alternatives (table 2) [5], recognizing that cities may not have mechanisms for valuing non-market services contributed by NBS. Two examples of this research approach include studies of green roofs and studies of nature-based coastal defences. Studies of the costs and benefits of green roofs have compared green roofs against those of reflective ‘cool’ roof alternatives, where costs included installation, maintenance and replacement costs, along with heating costs during cool times of the year, while benefits included reductions in energy use, avoided morbidity and mortality, and other health benefits from cooling, as well as reductions in stormwater runoff and air pollution [126,127]. Considering environmental context is critical, since cooling roofs will increase heating costs more in regions with colder climates and green roofs will increase irrigation costs more in regions with drier climates [126]. A synthesis of cost–benefit analyses of coastal defences worldwide showed that coastal habitats have high potential for protecting coastlines from flooding and erosion [128], and that salt marshes and coral reefs can be two to five times more cost-effective than engineered structures in protecting coastlines. These examples provide models for research analysing costs and benefits of implementing NBS to address climate change impacts.

(c) Are the benefits of nature-based strategies distributed equitably within and across cities?

Those who are most likely to experience climate change impacts within and across cities may also be those with the least access to nature-based relief from those impacts. Poorer communities within cities often are more vulnerable to climate change hazards because their members live or work in high-exposure areas and because they may lack the resources to adapt to climate change (e.g. air conditioning, adequate shelter or drainage). In addition, urban green spaces such as parks are more accessible to wealthy, white, able-bodied urban residents [129]. Similarly, tree canopy cover is often concentrated in wealthier neighbourhoods [130]. For example, many cities in the Amazon delta are experiencing rapid urbanization; these communities are highly vulnerable to flooding and contaminated water. Informal settlements, in particular, concentrate the urban poor in flood-prone areas that lack basic sanitation and water infrastructure [6]. This pattern repeats globally, with rapidly expanding cities in the decolonized world surrounded by unplanned settlements that develop an informal infrastructure that is rarely adequate to protect their inhabitants, while wealthy urban residents enjoy benefits of higher ground, adequate infrastructure or access to green space [131].

There is some hope that small-scale NBS can provide solutions to large disparities in vulnerability, if appropriate to the particular location [132]. However, a lurking challenge is the green gentrification that can accompany nature-based strategy implementation. New inequities often arise in urban greening projects when underprivileged people are denied access or representation (in planning and decision-making on siting of nature-based projects), or are edged out by deliberate attraction of high-income clients to newly constructed green space [133,134]. To ensure that all voices are heard in decision-making about NBS and that access and distribution are fair, deliberate policies that avoid green gentrification need to be developed in concert with urban planning. Kabisch *et al.* [135] outline four recommendations to ensure environmental justice in planning for urban green spaces: that the distribution of green spaces ensures equitable access; that efforts are made to give voice to all members of the population, including underrepresented groups; that interactions and social exchanges are open and safe; and that local characteristics are considered.

Across cities, NBS may be less effective in cities that will be most exposed to climate change hazards. Many cities in the Global South are equatorial, where rising temperature is more likely to cross tolerance thresholds. Many of these cities are also located in low-lying coastal areas and thus are vulnerable to storms and sea-level rise. Finally, cities in the Global South are rapidly growing and many lack financial means to keep up with construction of basic critical infrastructure, let alone combat the impacts of climate change through the construction of adequate protective infrastructure or design or preservation of NBS [74,75]. Without major acceleration of climate change mitigation, these cities may become unliveable and no magnitude of nature-based strategy implementation can sufficiently reduce the hazards they face. Yet, in others, NBS may provide a means to accelerate improvement of living conditions (table 2). Goal 11 of the Sustainable Development Goals adopted by the United Nations [136] pertains to sustainable cities and communities.

Of the 10 targets for Goal 11, three relate specifically to NBS: increase access to green space, reduce loss of lives and livelihoods from disaster, and increase city planning to create safe, inclusive, resilient and sustainable cities.

7. Conclusion

In this paper, we have considered how cities may amplify the hazards of climate change to SET components of cities. NBS have potential to reduce climate-change-related hazards directly; to dampen, rather than amplify, their effects on cities; and to minimize SET impacts. Reaching that potential requires fundamental research to understand the mechanisms that lead to amplification of hazards in cities and to quantify the conditions under which NBS will be effective. Researchers and practitioners must also understand fully the costs and benefits of green-infrastructure approaches to adapting cities to a changing climate, including both disservices and co-benefits, relative to traditional, grey approaches. We need a much-improved awareness of and commitment to ensuring that the most vulnerable populations within and among cities are not neglected, as proactive plans are developed to build social–ecological–technological resilience to the challenges posed by a rapidly changing climate. Finally, we conclude that NBS to meet climate-related challenges are most likely to be effective when they match the scale of the challenge and are appropriate to a specific place, in terms of its social, cultural, ecological and technological milieu.

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Endnote

[1] Throughout, we use adaptation, hazards, impacts, vulnerability and exposure according to the definitions of Field *et al.* [1].

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