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Social-ecological and technological factors moderate the value of urban nature

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Urban nature has the potential to improve air and water quality, mitigate flooding, enhance physical and mental health, and promote social and cultural well-being. However, the value of urban ecosystem services remains highly uncertain, especially across the diverse social, ecological and technological contexts represented in cities around the world. We review and synthesize research on the contextual factors that moderate the value and equitable distribution of ten of the most commonly cited urban ecosystem services. Our work helps to identify strategies to more efficiently, effectively and equitably implement nature-based solutions.

Two out of every three people will live in urban areas by 2050, meaning that the continued development of cities will increasingly shape human well-being[1]. Many of our greatest social and environmental challenges, such as climate change, public health and resource availability will be determined by the form, pattern and function of urban environments[2] — requiring massive financial investments. An estimated US$50–64 trillion will be invested globally in new urban infrastructure by the year 2030, with an additional US$2.4 trillion per year needed to implement the United Nations Sustainable Development Goals[3,4]. With rapid urbanization and growing needs for infrastructure, the paths taken for urban development in the next decade will have implications for both social and natural systems. This is reflected in the inclusion of 'sustainable cities and communities' as one of the 17 global goals for 2030. Addressing the challenge of sustainable development in cities requires balancing multiple, often conflicting, objectives with limited resources: equitable communities, economic development, sufficient food, water and energy, opportunities for recreation and renewal, and reduced risks to disasters.

Given the complex sustainability challenges facing urban areas, city leaders are in need of creative solutions, especially actions that are cost-effective and deliver multiple benefits. A growing number of cities are exploring 'nature-based solutions' that aim to promote public health and safety, enhance liveability, and restore natural hydrologic and ecological processes[5,6]. Actions considered under the broad umbrella of 'nature-based solutions' include tree-planting campaigns, new or improved parks or open spaces, implementing stormwater controls such as bioswales or retention ponds, restoration of urban rivers or streams, installation of green roofs or rain gardens, urban agriculture, and living shorelines (Table 1). Beyond their intended roles in retaining stormwater or providing shade and regulating climate, parks and green spaces in our cities often provide the only opportunity to experience nature for much of the world's population[7–9] and are essential habitats for urban biodiversity[10,11].

The extent to which specific nature-based solutions address urban sustainable development across and within diverse cities remains largely unknown[12]. Given limited resources and the heterogeneity of urban contexts and challenges, how much should different cities invest in nature-based solutions, and what kinds of benefits can they expect to receive? Our aim is to synthesize the existing evidence for where and when investments in the protection, enhancement or restoration of urban nature are most likely to support sustainable cities and communities.

Current understanding of the positive and negative impacts of nature-based solutions in cities is largely informed by research in urban ecology, urban forestry and environmental engineering. Introduction of the interdisciplinary concept of 'ecosystem services' — the goods and services people derive from nature — has elevated the potential economic value of urban nature[13,14]. Emphasizing links between urban nature and human well-being, the ecosystem services approach offers considerable promise for understanding where and when nature-based solutions will deliver a suite of services. However, there are limitations to the existing body of urban ecosystem services research that may reduce the adoption of specific interventions. Three key limitations, outlined below, motivated our review and synthesis.

The first limitation is that most urban ecosystem services assessments focus on one or two services associated with a limited set of nature-based solutions — most often street trees[15]. In their review, Haase et al.[16] found that 60% of reviewed studies on urban ecosystem services focused on a single service, most commonly air quality (16% of all entries) and carbon sequestration (12% of all entries). With notable exceptions[13,17–19], few studies investigated co-benefits, disservices, or the equity and distributional consequences of

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Table 1 | Urban ecosystem services and nature-based solutions

Urban ecosystem services	Nature-based solutions						
	Street trees	Parks and open space	Engineered stormwater controls[a]	Green roofs	Waterways and wetlands	Coastal habitats[b]	Urban gardens
Urban air quality	X	X					
Carbon sequestration	X	X					
Coastal protection						X	
Urban heat and heat extremes mitigation	X	X		X			
Stormwater and wastewater management	X	X	X	X	X		
Urban water supply	X	X	X				
Riverine flood impact reduction		X	X		X		
Recreation opportunities		X			X	X	
Mental health	X	X					X
Urban agriculture		X					X

We reviewed literature pertaining to ten ecosystem services associated with seven nature-based solutions. Gaps in this matrix identify combinations where there was not sufficient literature to review the impact of a specific solution on a given service and/or the nature-based solution has been determined to be minimally effective with respect to a particular ecosystem service. [a]Such as bioswales, rain gardens, retention ponds. [b]Such as oyster reefs, mangroves, dunes, marshes.

nature-based solutions. Not accounting for unintended consequences, positive or negative, risks undervaluing benefits or, worse, recommending interventions that put people or property at risk[20].

Second, the role of social, ecological and technological context in influencing the value of nature-based interventions is often overlooked[21,22]. As a result, we know little about the generalizability of findings across spatial and temporal scales, climates, cultures, or type and quality of built infrastructure[23,24]. Past studies have reported annual net benefits of urban trees from US$5 to $402 per tree — a range that suggests high uncertainty in both methodologies used to assess value and the expected returns of urban nature across diverse contexts[25,26].

Third, the value of nature-based solutions is rarely compared with alternative interventions that seek to improve well-being and reduce exposure to threats such as pollution[27]. Cities need actionable information that presents urban nature in comparable terms with traditional 'grey' infrastructure or technological solutions[28]. Putting nature on a level playing field with other interventions requires comparative information that allows decision-makers to juxtapose costs and effectiveness of different urban development pathways — including potential co-benefits and disservices in terms of human well-being at different scales[29,30]. Likewise, these recommendations need to be flexible in their relevance to individual cities and even neighbourhoods within cities. City leaders may not need detailed cost–benefit assessments for all alternatives, but do want to know which approaches are most likely to succeed under certain conditions and when nature should be considered as an effective solution to addressing urban sustainability challenges[31].

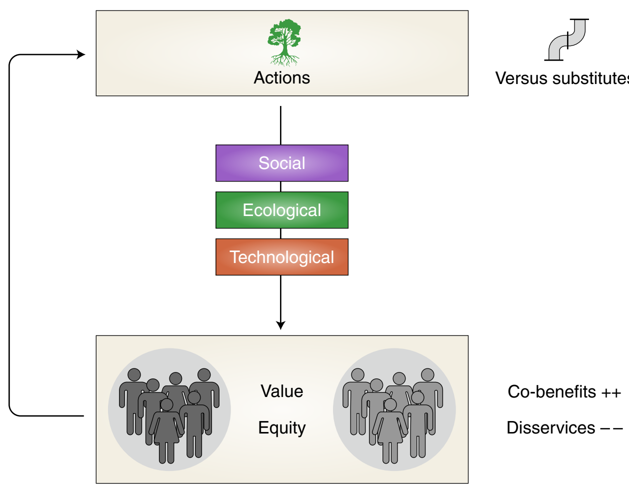

Fig. 1 | A framework for analysing the value of urban nature-based solutions. Actions lead to changes in the value of urban ecosystem services, defined by a change in human well-being, which may be different for different groups of people, hence the importance of considering equity. The relationships between actions and value are moderated by social, ecological or technological factors. For each action that leads to a change in value, there may also be co-benefits (for example, positive impacts on other sustainability goals) and disservices (for example, unintended negative consequences). Finally, decision-makers require the ability to compare the net value of urban ecosystem services relative to substitutes or alternative interventions designed to meet the same goals.

A framework for valuing urban nature

We adopted a common framework for our review and synthesis, focusing on how specific actions designed to affect urban ecosystem service values are moderated by social, ecological and technological factors (Fig. 1). We define 'social' as including socio-demographic variables, individual attitudes and beliefs, as well as governance, cultural and institutional factors that affect the exposure, vulnerability and preferences of residents to changes in urban ecosystem services[32]. 'Ecological' covers a broad range of biophysical factors, including climate, species, soils, geology and topography[27]. 'Technological' considers the type, quality and configuration of infrastructure, buildings and other human-engineered amenities[24].

The value of a change in urban ecosystem services is highly dependent on whose values are included and how value is defined and measured[33]. The term value can be used to refer to guiding principles, often referred to as underlying values or held values, which motivate the beliefs, actions and behaviours of individuals[34]. We adopt an economic definition of value, referring to a measure of worth or well-being that can be quantified in monetary terms (for example, avoided treatment costs) as well as non-monetary metrics such as changes in physical and mental health, social cohesion or perceived good quality of life[35,36]. For example, the value of a proposed redevelopment employing tree trenches, rain gardens and bioswales could be expressed narrowly in terms of the monetary savings of avoided water treatment or more broadly and diversely to also include potential co-benefits (for example, improved aesthetic quality or social cohesion) or disservices (for example, displacement of prior residents or an increased risk of pollen-related allergies).

A focus on the value of urban ecosystem services necessitates a more explicit consideration of the factors that either enhance or reduce equity in how services are realized by urban residents[37]. The value of nature-based solutions may not accrue equally to all residents or may result in unintended consequences such as gentrification[38]. We also highlight the importance of comparing the value of urban ecosystem services relative to non-nature substitutes or alternative interventions that achieve similar goals of improving the health, safety and liveability of cities (Fig. 1). This framing places the value of urban ecosystem services relative to infrastructure upgrades, technological solutions or behavioural modifications in terms of effectiveness in achieving sustainability targets.

Our work builds on recent reviews of nature-based solutions[17,18,39], with a unique focus on contextual factors, equity and distributional impacts, and the value of urban nature relative to non-nature substitutes. We reviewed a broad and interdisciplinary literature, with over 1,200 unique references cited in detailed reviews in the Supplementary Information of ten of the most commonly cited urban ecosystem services[16] associated with seven types of nature-based solutions (Table 1). Teams of experts applied the synthesis framework (Fig. 1) to each urban ecosystem service — identifying literature that reported on social, ecological and technological factors affecting the value of urban nature along with equity implications, co-benefits and disservices, potential alternatives or substitutes to nature-based solutions, recommendations for practitioners, and relevant tools or models for estimating the value of urban ecosystem services. Authors synthesized their findings into a set of reviews included as Supplementary Information designed to serve as both stand-alone documents for an audience of practitioners and urban researchers, as well as the basis for the cross-service synthesis presented here in the main text. Findings across all reviews are synthesized in Table 2, which also includes an assessment of uncertainty and the potential magnitude or impact of nature-based solutions on each ecosystem service.

Context determines nature's values

In this section, we highlight some of the social, ecological and technological factors identified as most influential in determining the values of urban nature. We point readers to the reviews in the Supplementary Information for additional content organized by individual urban ecosystem service.

Social context. Social factors vary both within and among cities and moderate the exposure to, access to and value of nature-based solutions[32]. Our review identified social and cultural norms, income and demographics, and institutional and financial capacity as the dominant social moderators of the value of urban nature[40].

For recreational and cultural services provided by urban nature, we found demographics and cultural identity, and perceptions of inclusivity and ownership identified as key social moderators[41–43]. Research identified that community or private gardens may be viewed as either assets or 'unkempt' spaces, depending on individual preferences and how gardens are managed[44,45]. Similarly, studies found that individuals see parks and green spaces as either inviting or unsafe spaces, depending on past experiences[46,47]. Research shows female users are more likely to consider safety as a constraint to recreation in urban parks than male users[48]. These examples illustrate that perceptions of safety and a sense of belonging, not just physical access to urban nature, determine how urban green spaces are used and valued[30,49]. Cultural norms can also enhance urban recreation, for example, in Japan, where 'forest bathing' is a common cultural practice[50].

Income, education and financial resources were frequently cited constraints on the funding and implementation of nature-based solutions, as well as the capacity to model, monitor and maintain green infrastructure over time[51]. Long-term maintenance of green infrastructure in the form of watering, removal of leaves or debris, or picking up trash is often needed to maximize benefits and improve performance. Less-developed or more rapidly developing urban areas may not have the same capacity — financial resources, access to credit, or awareness of the need for upkeep and maintenance — which in turn affects the value that nature provides to different residents[52–54]. While cities or non-governmental organizations often cover implementation costs, maintenance responsibilities — especially watering costs — can fall to residents, further burdening lower-income neighbourhoods[31]. Our review underscores how the long-term durability of nature-based solutions is driven by local buy-in and institutional and community capacity[55].

Demography and income also affect the vulnerability of residents to changes in urban ecosystem services and the subsequent distribution of benefits or costs. Younger and older members of an urban population and those with disabilities and/or other health issues may have few opportunities to relocate away from heatwaves, floods or pollution, or to evacuate in the short term, thus making nature-based solutions more important for the well-being of high-risk residents[56]. Furthermore, neighbourhoods with low literacy, and limited access to information may be less equipped to respond to early warning systems and have lower awareness of the impacts of air or water pollution[57]. Access to in-home air conditioning and high-quality and well-insulated housing can also make some populations less susceptible to heatwaves and increased energy costs[58,59].

Ecological and biophysical context. Of the numerous biophysical factors that influence the value of urban nature, vegetation structure and function, topography and landscape position, and geologic and soil characteristics were the most frequently documented contextual moderators across our reviews (Table 2).

The structure, form and phenology of urban vegetation was especially important for regulating the effects of nature-based solutions on urban air quality, heat mitigation, carbon sequestration, coastal protection and flood mitigation[27,60]. Species traits such as larger leaf area and sticky or hairy leaves increase the removal rate of particulate air pollution[61]. Canopy density, productivity and rates of evapotranspiration enhance the effect of tree cover on shade provision, heat mitigation and reduced energy consumption[62,63]. Denser, taller, wider and more continuous habitats provide more coastal protection[64], and vegetation that has high roughness is the most effective at slowing overland flow of stormwater runoff[65]. Species root depth and structure influences infiltration and retention of nutrients, and leaf nutrient content and phenology affect the amount and timing of nutrient export to stormwater systems[65,66].

The potential for implementing nature-based solutions is also highly dependent on the physical space available for green infrastructure, especially in urban environments where space is often at a premium[67]. Urban heat mitigation, for example, requires a minimum green space of 0.5 to 2.0 ha to significantly alter air temperature at the neighbourhood scale[68,69]. Coastal habitat protection against storm surge and treating stormwater with green infrastructure (for example, rain gardens and bioswales) requires more available space than comparable grey approaches[70,71].

The spatial configuration and landscape position of nature-based solutions also determines the value of these solutions. Coastal habitats are more effective at stabilizing shorelines when located along sheltered coasts or bays subject to lower intensity coastal hazards[72]. Wetlands and floodplains are most effective when located downstream of major sources of runoff production, such as where there are large and highly impervious upstream contributing areas[73].

Soil and geological factors were important for all of the hydrologic services, including riverine flood mitigation, coastal protection, stormwater and wastewater management, and urban

Table 2 | Synthesis of key insights from across the individual urban ecosystem service reviews

Urban ecosystem services	Dominant social, ecological and technological factors that affect the value of urban nature-based solutions	Potential value (low, moderate, high) and uncertainty (low, moderate, high)	Non-nature substitutes
Urban air quality	Presence of threat: air pollution Location, size and configuration of vegetation at the city-block scale Vegetation structure and function: leaf area, canopy structure and volatile organic compound production Socioeconomic: age, health	Low potential value Low to moderate uncertainty	Non-vegetated barriers, pollution-reduction strategies such as fuel switching, fuel efficiency standards, traffic control or point-source reductions
Carbon sequestration	Location, size and configuration of vegetation Vegetation structure and function: productivity and shade provision Management: energy consumed in tree planting and maintenance Socioeconomic: energy portfolio, insulation, income	Low potential value Low uncertainty	Carbon capture and storage, bioengineering, carbon mitigation activities including fuel switching, renewable energy and other point-source reductions
Coastal protection	Presence of threat: frequency and intensity of storm surge, sea-level rise Location and configuration of coastal habitat relative to shoreline Vegetation structure and function: stand density, height, width and contiguity Topography: slope, geology, soils Socioeconomic: age, income, housing quality, access to transportation, literacy and language	Moderate to high potential value Moderate uncertainty	Built coastal infrastructure such as seawalls, levees, bulkheads, jetties and groins
Urban heat and heat extremes mitigation	Presence of threat: extreme heat events, rising average temperatures Location, size and configuration of vegetation at the city-block scale Vegetation structure and function: canopy density, evapotranspiration Socioeconomic: age, health, income, presence of air conditioning	Moderate to high potential value Moderate uncertainty	Cooling centres; air conditioning in homes; residential and commercial insulation retrofits; white or 'cool' roofs
Stormwater and wastewater management	Presence of threat: frequency and intensity of storm events or combined sewage overflows Location, size and configuration of vegetation at watershed scale Vegetation structure and function: evapotranspiration, root structure Infrastructure: type, quality and density of stormwater infrastructure Topography: slope and geology/soils Socioeconomic: elevation, housing quality, income	Low to high potential value Moderate uncertainty	Centralized wastewater and stormwater drains and treatment plants; built structures to increase infiltration, drainage or control runoff (including rainwater harvesting)
Urban water supply	Location, size and configuration of vegetation at city scale Vegetation structure and function: evapotranspiration, root structure Infrastructure: presence of reservoirs or wells Topography: slope, geology, soils Socioeconomic: population, income, lack of access to treatment or water infrastructure	Low potential value Low to moderate uncertainty	Rainwater harvesting; desalination plants; water treatment, water recycling; piped water coming from surrounding regions (including interbasin transfer schemes)
Riverine flood impact reduction	Presence of threat: frequency and intensity of storm events Location, size and configuration of vegetation at watershed scale Vegetation structure and function: evapotranspiration, root structure Infrastructure: type, quality and density of built flood control devices Topography: slope, geology, soils Socioeconomic: elevation, housing quality, income	Moderate to high potential value Moderate uncertainty	Levees, dykes and other barriers to flood waters; channel straightening to move water quickly out of cities; riprap to armour riverbanks; flood-proofing of homes or managed retreat
Recreation opportunities	Location, size and configuration of urban nature at neighbourhood scale Access Programming, maintenance, built amenities that are sensitive to cultural norms and social preferences, public safety. Socioeconomic: income, age, gender, culture	Moderate to high potential value Low to moderate uncertainty	Virtual environments or simulated natural places, non-nature-based recreation activities (for example, art, culture, sporting events)

Continued

Table 2 | Synthesis of key insights from across the individual urban ecosystem service reviews (Continued)

Urban ecosystem services	Dominant social, ecological and technological factors that affect the value of urban nature-based solutions	Potential value (low, moderate, high) and uncertainty (low, moderate, high)	Non-nature substitutes
Mental health	Presence of threat: baseline level of stress, need for restoration and improvement of cognitive function and affect Location, size and configuration of urban nature at neighbourhood scale Access Socioeconomic: income, cultural norms, affinity for nature, health	Low to high potential value High uncertainty	Mediated nature experiences (through pictures, videos); psychiatric, psychological and medical treatments and therapies; other well-being programmes through healthcare facilities, employment programmes and so on
Urban agriculture	Location, size and configuration of urban agriculture at city block and neighbourhood scale Access to land, including plots without soil contamination, access to food production Infrastructure: irrigation Cultural relevance of crops grown and role of community organizers Socioeconomic: presence of food insecurity or malnutrition, recreational or income-generating nature, neighbourhood aesthetics	Variable: as food provisioning service, low to moderate potential value; as cultural service, moderate value Moderate uncertainty	Rural agriculture, technological alternatives in urban areas (rooftop greenhouses, hydroponic agriculture, vertical farms), mobile food markets and vendors

For each urban ecosystem service, we highlight the social, ecological and technological factors found to be most important in moderating the value of urban nature. Subsequent columns summarize the potential magnitude of the value of urban nature and associated uncertainty, and the most frequently discussed non-nature substitutes. There are several contextual factors that are important across all urban ecosystem services including the size and available space for urban nature and the number and location of potential beneficiaries, both which scale positively with value. Similarly, social norms, cultural preferences, and the management or stewardship of urban nature may affect both the performance and perceived value of urban nature. Climate is an important contextual factor that interacts with all services, positively and negatively. Expanded reviews for each urban ecosystem service are provided in the Supplementary Information.

water supply. In general, compact soils, high rates of imperviousness and steep slopes inhibit infiltration and reduce the effectiveness of nature-based solutions to mitigate flooding and enhance water recharge[74].

Other than a few studies that examined the role of biodiversity in green spaces in determining the frequency and duration of visits to urban nature[75,76], we found little discussion of how biophysical factors moderate the value of mental health and recreation services. This is in part due to disciplinary conventions in the psychology and leisure studies literature that rarely investigate or report on variability in the form, structure or composition of urban nature[77]. This gap leaves urban practitioners with a limited understanding of the 'nature of the nature' that provides valuable cultural services.

Technological context. Patterns of urban development, particularly existing infrastructure such as stormwater and sanitary sewers, levees, river channelization projects, or bank armouring, modify the supply of and demand for urban ecosystem services[22,24]. The value of green infrastructure declines if water supply services have already been replaced by built infrastructure, such as reservoirs that store water efficiently, or alternative sources of water supply such as desalination plants[73]. In the absence of built infrastructure, sustaining high baseflow levels in surface waters through infiltration is critical to provide year-round supply. Similarly, the existence of flood-control infrastructure such as levees, river channelization or bank armouring can reduce the demand for flood-damage mitigation services provided by urban nature. These past infrastructure investments create path dependencies that can limit the space available for urban nature, reduce demand for the services provided by green infrastructure or decrease its effectiveness relative to grey alternatives[78].

The effectiveness of nature-based solutions is likely to be maximized under specific infrastructure conditions. Cities with combined sewer infrastructure have greater risks of sewage overflows, which bring stormwater runoff and sewage into streets, neighbourhoods, and receiving urban streams and lakes. In these cities, bioswales, street trees and rain gardens can intercept, evaporate and infiltrate stormwater before it reaches sewer systems and decrease the volume of water treated in wastewater treatment facilities[79,80]. In cities with separated sanitary and stormwater sewers, stormwater runoff is typically untreated before discharge to receiving lakes or rivers. In these systems, green infrastructure provides the only treatment for stormwater, retaining pollutants and providing infiltration services that may improve aquatic habitat, reduce rates of water-borne disease transmission and reduce downstream flooding[80]. Cities where a large proportion of residents lack access to piped infrastructure could be expected to see large benefits from nature-based investments, especially to human health. Older cities and new, rapidly urbanizing areas that lack large-scale water infrastructure may see the greatest benefits from urban nature, relative to cities where heavy investments in infrastructure upgrades have already been made[78].

Specific types of infrastructure within or in connection to urban nature affect how these spaces are used, which influences access. For example, walking paths or loops correspond with park use and increases in physical activity among users[81]. Transit (for example, whether public transportation options are available or whether a car is required for access), parking policies, hours of operation, and whether or not there are fees associated with use (for example, for entrance, parking or use of shelters) determine accessibility and associated benefits of urban green and blue spaces for urban residents[82]. Built infrastructure can also impede access to recreation opportunities provided by urban green and blue spaces[83] or, if improperly maintained, serve as a deterrent to park use[84].

Interactions among social, ecological and technological factors affect the subsequent value of urban ecosystem services. We found that some factors, such as climate change, can affect multiple services, but in different ways. Changes in the frequency and intensity of precipitation in the form of floods or droughts can simultaneously overwhelm infrastructure, increase water and energy demand, affect the productivity of urban vegetation, and exacerbate social and cultural divisions that can promote unrest or instability[85]. Climate impacts on urban temperatures can affect wind speed and direction and accelerate the rate of chemical reactions that determine the concentration of pollutants in the urban environment[61,86] or make urban waters more susceptible to harmful algal blooms[87]. In yet another example of a complex climate-related interaction, wealthier cities or neighbourhoods who devote greater resources to the maintenance of urban nature through trimming, irrigation and collection of leaf litter or debris can decrease or even reverse the net carbon benefits of vegetation due to the energy and fuel consumption embedded in these activities[88].

The value of nature-based solutions is also determined by the presence and intensity of external threats such as pollution, flooding, heat or mental stress that increase the demand for urban ecosystem services (Table 2). For example, urbanization has been associated with increased incidence of mental health disorders, including anxiety disorders and depression[89,90]. The services provided by urban nature via improved mood and cognitive function will have the greatest net value in cities where stress rates are high and the need for restoration is greatest. Greater threats don't necessarily correlate with improved ecosystem services in all cases. Urban nature may provide limited coastal protection, riverine flooding or stormwater management services under high-intensity rain or flood events, because higher-intensity storms saturate the interception capacity of trees or overwhelm coastal habitats[91].

Equity and distributional implications

The distributional implications of nature-based solutions are critically important to assess urban sustainability as they help to identify who benefits from investments in urban nature. We identified three different dimensions of equity critical to understanding the value of urban nature: differences in exposure to environmental harms or access to benefits, policies and processes that lead to unequal environmental outcomes for different communities, and unequal distribution of assets and financial resources between groups of people, influencing the ability to mitigate risks or acquire substitutes for urban ecosystem services[56].

Our review revealed consistent patterns of unequal exposure to environmental risks across a range of urban ecosystem services, where low-income and minority communities have greater exposure to air and water pollution, floods, and other extreme events[92,93]. Access to the benefits of urban nature is also unequally distributed within cities[94]. Research has shown that higher-quality and safer parks tend to be located close to wealthier neighbourhoods, rather than near low-income and ethnic-minority communities[95]. Demographics also affect relative risk to environmental harms. In general, children, the elderly, the poor and those with chronic illness are most in need of or will benefit the most from targeted strategies that adapt to or mitigate against floods, pollution or heatwaves[96,97].

Policies and processes aimed at increasing green spaces in cities can interact with social and demographic factors that exacerbate harms or create unintended consequences. Gentrification in the wake of new green space developments or upgrades, for example, is a growing environmental justice concern in cities of the developed and developing world[38,98].

For example, in Seoul, South Korea, the price of housing increased most quickly around newly constructed parks[99]. In Barcelona, Spain, similar increases in housing prices were associated with decreases in the number of older[89,90], poorer and more vulnerable people in neighbourhoods surrounding new parks[100]. In Bangalore, India, restoration of urban lakes that are traditionally used for religious ceremonies and fishing has led to new restrictions on lake use, which exacerbates inequities in access, and disadvantages low-income communities who rely on the lakes for their livelihoods and cultural services[101,102].

The unequal distribution of wealth affects the ability of urban dwellers to access substitutes such as air conditioning or treated water, which may mitigate against exposure to heat or pollution. In low-income communities, lack of in-home air conditioning and poor housing quality increases the vulnerability of residents to heat and associated health impacts[103,104]. Poorer residents are also more dependent on public spaces for exercising and recreation, even if green spaces in their neighbourhoods lack proper maintenance or have fewer amenities[105]. In contrast, higher-income residents are more likely to have access to private green spaces (for example, lawns, gardens) and high-quality public spaces with more amenities. Higher-income households are able to purchase alternative sources of entertainment or recreation, or have the leisure time and means to travel outside the city to seek nature-based recreation[106,107].

Our review also identified examples where nature has empowered marginalized groups to create more equitable green spaces, neighbourhoods and cities. Community gardens and other urban green spaces — if designed inclusively — can improve community cohesion and strengthen social networks across diverse groups[108]. For instance, new immigrants to Toronto, Canada, credit urban gardening for providing culturally appropriate food sources and more inclusive public spaces[109]. Cross-sectional work indicates that nature experience may benefit those from disadvantaged backgrounds more than those from advantaged ones, which could reduce inequities in mental health and other outcomes across socioeconomic groups[110,111]. Because poorer neighbourhoods are more likely to be deprived of safe, accessible green spaces, the relative contribution of urban nature to recreation, social cohesion and other cultural services in low-income areas may be among the most efficient and equitable solutions to improve the well-being of urban residents[112].

Co-benefits and disservices

Nature-based solutions hold promise over built or technological alternatives, especially when co-benefits can be easily recognized and quantified[6,17]. Accounting for multiple ecosystem service benefits can identify opportunities for cost sharing and build broader coalitions of support, essential to the long-term success of nature-based solutions. For example, parks can double as water collection basins and mitigate urban warming in addition to providing recreational and cultural opportunities. In some cities, rivers, lakes and green spaces are used for cultural practices and religious rites, as well as a source of food, medicines and livelihoods[113,114]. In many cities around the world, protecting and enhancing natural areas within the city limits will have the added co-benefit of providing and improving habitat for wildlife, contributing significantly to biodiversity conservation, attracting tourism and small businesses, and providing valuable educational or research opportunities[10].

Ecosystem disservices, or negative trade-offs associated with nature-based solutions, can also affect the relative value of urban nature compared with alternative investments[115]. Urban vegetation often requires supplemental irrigation, with street trees, urban agriculture and park vegetation potentially consuming more water than they infiltrate, a disservice that may be significant in dry environments where water resources are scarce[116,117]. An analysis of water balance in Los Angeles, California, found that up to 70% of evapotranspiration in the city could be attributed to urban lawns and turfgrass[118]. Tree roots or limbs can damage pavement and other infrastructure, leading to costly repairs and legal expenses[25]. Trees and urban vegetation can be sources of nutrient pollution, as well as harmful pests, pollen allergens and volatile organic compounds that may cause health problems[119,120]. Street trees planted in urban canyons can reduce ventilation, effectively trapping vehicle emissions at the pedestrian level[61]. Urban nature also can be a source of contaminants: trees adjacent to impervious surfaces contribute nutrients to surface waters; wetlands can be sources of nutrients if not engineered and maintained properly; turfgrass lawns can contribute nutrients in runoff; and engineered stormwater ponds can concentrate toxins and be sources of soluble nutrients[121].

The examples of co-benefits and trade-offs described above represent a minority of urban ecosystem studies we reviewed. Most papers did not consider that parks and green infrastructure can have unintended negative effects or failed to explore potential interactions — positive or negative — that affect ecosystem service value. An expanded discussion of potential co-benefits and disservices associated with the seven types of nature-based solutions we reviewed is included in Supplementary Table 1.

Urban nature compared with substitutes

The value of nature-based solutions can be measured against alternative interventions that can meet the same goals, such as improved health, reduced air and water pollution, and climate mitigation. Substitutes for the infiltration and water supply benefits of urban nature include treatment facilities, desalination plants, water reuse systems and reservoirs. The demand for urban cooling can be met through shade provision and enhanced tree cover, or through indoor air conditioning and access to urban cooling centres.

Previous studies have cautioned against overselling the value of nature-based solutions, especially where green infrastructure competes for funding with other interventions aimed at improving the health and sustainability of cities[6,27]. For example, restored wetlands can improve water quality and flood control but are no substitute for sewage treatment[122]. Trees can mitigate air pollution under some conditions but the contribution of trees to reductions in air pollution at the city scale is minimal, ranging from less than 1% to up to 5% (refs. [60,123]). Recent analyses suggest that reductions in carbon emissions and particulate air pollution could be more effectively and permanently addressed by reducing energy consumption in cities or switching to cleaner energy technologies[124,125].

Another commonly cited limitation of nature-based solutions, relative to engineered devices, is that their effectiveness is limited by available space. Unless they have a specific engineered design, street trees infiltrate a small volume of water, whereas engineered solutions are designed to collect large amounts of stormwater from surrounding areas[126]. Forested areas or green infrastructure can reduce runoff production for small storms, but their effect is negligible for events higher than 20% mean annual flood[127]. In general, urban vegetation is more effective in reducing flood peaks under lower-magnitude and lower-intensity rainfall events[128]. Grey infrastructure can also fail under extreme conditions, with sometimes disastrous effects, but in general, built solutions can be engineered to accommodate larger-intensity events relative to nature-based solutions.

For some services, non-nature substitutes may be readily available in some neighbourhoods and limited in others. In the case of food provision, substitutes are available in the form of foods imported from outside the city, provided that individual urban consumers have purchasing power and access to food vendors and retailers; the relative potential and benefits of sourcing foods within cities will depend on a variety of factors, including climate, farmer skill level and access to productive resources — especially land[129,130]. Similarly, the psychological and social benefits of nature-based recreation in cities may not have substitutes in the same way that grey infrastructure can provide urban water management services or pollution control technologies can improve air quality[131]. Outdoor recreation is perhaps the highest-valued ecosystem service in cities without a non-nature substitute[132]. A recent study supports this claim with survey results on the relative value of different types of cultural services provided by urban parks in Berlin, Germany, where most respondents "place a very high value" on recreation[133].

For most services, robust comparisons of the value of urban ecosystem services relative to substitutes are not available. Especially lacking are controlled studies that compare the performance of natural and built solutions under a range of conditions and over time, or studies examining the insurance value of natural ecosystems. There is evidence that uncertainty about the effectiveness of nature-based solutions is lower than for built infrastructure[134]. A systems approach that adopts a long-term perspective on the value of nature-based solutions, inclusive of co-benefits and disservices, is the only way to reliably compare green versus grey approaches to addressing urban sustainability challenges.

Perspectives and research frontiers

Our comprehensive review reveals the importance of social, ecological and technological context in moderating the value of urban nature, and identifies and summarizes these factors as they are addressed in the literature on ten different urban ecosystem services. Our synthesis is aimed at practitioners and researchers seeking to maximize the benefits of urban nature in an equitable manner, while minimizing unintended consequences (see Table 2 and the 'Recommendations for practitioners' sections at the end of each service review in the Supplementary Information). While we have carefully reviewed and summarized evidence across several contextual factors and services, many gaps remain.

Targeted research on the potential for urban nature to promote multiple dimensions of equity is needed to determine who stands to benefit from urban nature[135,136]. Incorporating equity, culture and governance factors into an urban ecosystem services assessment requires social science tools and approaches that are not yet mainstream in the ecosystem services community[137]. Also needed are advancements in how we estimate and communicate the value of nature as part of a portfolio of actions that include green, grey, social, institutional, behavioural and other yet-to-be discovered solutions.

Not covered in our review is a discussion of interactions between cities, indirect land uses and tele-coupling that links the consumption of urban dwellers with producers in rural and other urban areas around the world[2]. Nature outside the city contributes to ecosystem service benefits within the city in the form of food and resource recovery as well as disservices such as the transport of floodwaters and air pollution[138,139].

Perhaps the most critical gap in our understanding of the value of urban nature is the strikingly uneven distribution of research on urban ecosystem services, with the vast majority of studies concentrated in Europe, China and the United States[16,78,115]. Conclusions drawn from these high-income contexts are of limited utility in the regions of the world that are projected to experience the greatest and most rapid urban growth[140]. Nature-based solutions may look very different in the Global South where infrastructure and notions of public space are characterized by high levels of informality and decentralization[141]. An agenda for urban ecosystem services research must address these disparities to provide decision-relevant guidance for communities and leaders in pursuit of more equitable and sustainable cities across the world.

Achieving the United Nations Sustainable Development Goal for 'sustainable cities and communities' will require collaboration across disciplines and sectors, from engineering firms to policy and planning authorities at local, regional and national levels. While engineered solutions are, by definition, tailored to particular problems, nature-based solutions often provide multiple ecosystem services, but these benefits are much harder to estimate in traditional cost–benefit assessments. Our work calls for increased investment in research and decision support to help determine the right mix of nature-based solutions in the right place at the right scale to deliver benefits to communities and households that need them most. Models and tools that can assess ecosystem services at fine scales are relatively nascent in the urban literature and will be needed to determine distributional consequences at the household or neighbourhood scale. That said, it is unlikely there will ever be a generalizable toolkit for estimating the value of urban nature. As our review demonstrates, the same size, configuration and composition of urban nature may have positive, neutral or negative ecosystem service values because of specific social, ecological and technological contexts. Even as data availability and resolution improves, quantitative models may not be the most appropriate tools to evaluate ecosystem service values, especially equity concerns. Recognition of the importance of context necessitates more emphasis on localized place-based research that is historically, culturally and socially grounded, over one-size-fits-all decision support tools that aim to estimate the value of nature across different scales and contexts.

Urban nature clearly has value, but our synthesis suggests that when contextual moderators and co-benefits and disservices are not considered, the value of nature can be over- or underestimated. We conclude that greater research should be directed to nature-based solutions that: (1) deliver high value in specific contexts, (2) lack substitutes in grey or built infrastructure, or for which infrastructure can lead to negative consequences, and (3) have the greatest potential to directly improve the health, safety and well-being of vulnerable or marginalized populations. Such a reframing of the value of urban nature may suggest a shift in emphasis from research on specific goals such as mitigating air pollution or carbon emissions with street trees, towards greater investments in understanding the contributions of nature for recreation, social cohesion, and physical and mental health. Ongoing research on nature-based solutions across social, ecological and technological contexts will allow urban leaders to be much more strategic in the deployment of urban nature, in communicating its benefits and in maximizing nature's value where it matters most.

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References

1. *World Urbanization Prospects: The 2014 Revision* (United Nations, Department of Economic and Social Affairs, Population Division, 2014).
2. Seto, K. C., Golden, J. S., Alberti, M. & Turner, B. L. Sustainability in an urbanizing planet. *Proc. Natl Acad. Sci. USA* **114**, 8935–8938 (2017).
3. *The State of City Climate Finance 2015* (Cities Climate Finance Leadership Alliance, 2015).
4. Schmidt-Traub, G. *Investment Needs to Achieve the Sustainable Development Goals: Understanding the Billions and Trillions* Working Paper Version 2 (Sustainable Development Solutions Network, 2015).
5. Nesshöver, C. et al. The science, policy and practice of nature-based solutions: an interdisciplinary perspective. *Sci. Total Environ.* **579**, 1215–1227 (2017).
6. Depietri, Y. & McPhearson, T. in *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages between Science, Policy and Practice* (eds Kabisch, N., Korn, H., Stadler, J. & Bonn, A.) 91–109 (Springer, Cham, 2017).
7. Hartig, T. & Kahn, P. H. Living in cities, naturally. *Science* **352**, 938–40 (2016).
8. Soga, M. & Gaston, K. J. Extinction of experience: the loss of human–nature interactions. *Front. Ecol. Environ.* **14**, 94–101 (2016).
9. Cox, D. T. C., Hudson, H. L., Shanahan, D. F., Fuller, R. A. & Gaston, K. J. The rarity of direct experiences of nature in an urban population. *Landsc. Urban Plan.* **160**, 79–84 (2017).
10. Elmqvist, T. et al. *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities* (Springer, Cham, 2013).
11. Dunn, R. R., Gavin, M. C., Sanchez, M. C. & Solomon, J. N. The pigeon paradox: dependence of global conservation on urban nature. *Conserv. Biol.* **20**, 1814–1816 (2006).
12. Cortinovis, C. & Geneletti, D. Ecosystem services in urban plans: what is there, and what is still needed for better decisions. *Land Use Policy* **70**, 298–312 (2018).
13. Gómez-Baggethun, E. & Barton, D. N. Classifying and valuing ecosystem services for urban planning. *Ecol. Econ.* **86**, 235–245 (2013).
14. Bolund, P. & Hunhammar, S. Ecosystem services in urban areas. *Ecol. Econ.* **29**, 293–301 (1999).
15. Luederitz, C. et al. A review of urban ecosystem services: six key challenges for future research. *Ecosyst. Serv.* **14**, 98–112 (2015).
16. Haase, D. et al. A quantitative review of urban ecosystem service assessments: concepts, models, and implementation. *Ambio* **43**, 413–433 (2014).
17. Raymond, C. M. et al. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **77**, 15–24 (2017).
18. Kabisch, N., Qureshi, S. & Haase, D. Human–environment interactions in urban green spaces — a systematic review of contemporary issues and prospects for future research. *Environ. Impact Assess. Rev.* **50**, 25–34 (2015).
19. Salmond, J. A. et al. Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health* **15**(Suppl. 1), S36 (2016).
20. Ruckelshaus, M. H. et al. Evaluating the benefits of green infrastructure for coastal areas: location, location, location. *Coast. Manag.* **44**, 504–516 (2016).
21. Grimm, N. B., Cook, E. M., Hale, R. L. & Iwaniec, D. M. in *Routledge Handbook of Urbanization and Global Environmental Change* (eds Seto, K. C. et al.) 202–212 (2015).
22. McPhearson, T. et al. Advancing urban ecology toward a science of cities. *Bioscience* **66**, 198–212 (2016).
23. Kremer, P. et al. Key insights for the future of urban ecosystem services research. *Ecol. Soc.* **21**, 1–11 (2016).
24. Ramaswami, A. et al. A social–ecological–infrastructural systems framework for interdisciplinary study of sustainable city systems: an integrative curriculum across seven major disciplines. *J. Ind. Ecol.* **16**, 801–813 (2012).
25. Mullaney, J., Lucke, T. & Trueman, S. J. A review of benefits and challenges in growing street trees in paved urban environments. *Landsc. Urban Plan.* **134**, 157–166 (2015).
26. Hotte, N., Barron, S., Nesbitt, L., Cheng, Z. C. & Cowan, J. *The Social and Economic Values of Canada's Urban Forests: A National Synthesis* (UBC Faculty of Forestry, University of British Columbia, Forest Sciences Centre, 2015).
27. Pataki, D. E. et al. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Front. Ecol. Environ.* **9**, 27–36 (2011).
28. Baró, F., Haase, D., Gómez-Baggethun, E. & Frantzeskaki, N. Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. *Ecol. Indic.* **55**, 146–158 (2015).
29. Wachsmuth, D., Aldana Cohen, D. & Angelo, H. Expand the frontiers of urban sustainability. *Nature* **536**, 391–393 (2016).
30. Ordóñez-Barona, C. How different ethno-cultural groups value urban forests and its implications for managing urban nature in a multicultural landscape: a systematic review of the literature. *Urban For. Urban Green.* **26**, 65–77 (2017).
31. Pincetl, S., Gillespie, T., Pataki, D. E., Saatchi, S. & Saphores, J. D. Urban tree planting programs, function or fashion? Los Angeles and urban tree planting campaigns. *GeoJournal* **78**, 475–493 (2013).
32. Jones, R. E., Davis, K. L. & Bradford, J. The value of trees: factors influencing homeowner support for protecting local urban trees. *Environ. Behav.* **45**, 650–676 (2013).
33. Meerow, S. & Newell, J. P. Urban resilience for whom, what, when, where, and why? *Urban Geogr.* https://doi.org/10.1080/02723638.2016.1206395 (2016).
34. Ives, C. D. & Kendal, D. The role of social values in the management of ecological systems. *J. Environ. Manage.* **144**, 67–72 (2014).
35. Olander, L. P. et al. Benefit relevant indicators: ecosystem services measures that link ecological and social outcomes. *Ecol. Indic.* **85**, 1262–1272 (2018).
36. Pascual, U. et al. Valuing nature's contributions to people: the IPBES approach. *Curr. Opin. Environ. Sustain.* **26–27**, 7–16 (2017).
37. Jennings, V., Larson, L. & Yun, J. Advancing sustainability through urban green space: cultural ecosystem services, equity, and social determinants of health. *Int. J. Environ. Res. Public Health* **13**, 196 (2016).
38. Checker, M. Wiped out by the 'Greenwave': environmental gentrification and the paradoxical politics of urban sustainability. *City Soc.* **23**, 210–229 (2011).
39. van den Bosch, M. & Ode Sang, Å. Urban natural environments as nature-based solutions for improved public health — a systematic review of reviews. *Environ. Res.* **158**, 373–384 (2017).
40. Dempsey, N., Bramley, G., Power, S. & Brown, C. The social dimension of sustainable development: defining urban social sustainability. *Sustain. Dev.* **19**, 289–300 (2011).
41. Saldivar-Tanaka, L. Culturing neighborhood open space, civic agriculture, and community development: the case of Latino community gardens in New York City. *Agric. Hum. Values* **21**, 399–412 (2004).
42. Langemeyer, J., Camps-Calvet, M., Calvet-Mir, L., Barthel, S. & Gómez-Baggethun, E. Stewardship of urban ecosystem services: understanding the value(s) of urban gardens in Barcelona. *Landsc. Urban Plan.* **170**, 79–89 (2018).

43. Rupprecht, C. D. D. & Byrne, J. A. Informal urban green-space: comparison of quantity and characteristics in Brisbane, Australia and Sapporo, Japan. *PLoS ONE* **9**, e99784 (2014).
44. van den Berg, A. E. & van Winsum-Westra, M. Manicured, romantic, or wild? The relation between need for structure and preferences for garden styles. *Urban For. Urban Green.* **9**, 179–186 (2010).
45. Nassauer, J. I. Messy ecosystems, orderly frames. *Landsc. J.* **14**, 161–170 (1995).
46. Lin, B. B., Fuller, R. A., Bush, R., Gaston, K. J. & Shanahan, D. F. Opportunity or orientation? Who uses urban parks and why. *PLoS ONE* **9**, e87422 (2014).
47. Lapham, S. C. et al. How important is perception of safety to park use? A four-city survey. *Urban Stud.* **53**, 2624–2636 (2016).
48. Ghimire, R., Green, G. T., Poudyal, N. C. & Cordell, H. K. An analysis of perceived constraints to outdoor recreation. *J. Park Recreat. Admi.* **32**, 52–67 (2014).
49. Koppen, G., Sang, Å. O. & Tveit, M. S. Managing the potential for outdoor recreation: adequate mapping and measuring of accessibility to urban recreational landscapes. *Urban For. Urban Green.* **13**, 71–83 (2014).
50. Tsunetsugu, Y., Park, B. J. & Miyazaki, Y. Trends in research related to 'shinrin-yoku' (taking in the forest atmosphere or forest bathing) in Japan. *Environ. Health Prev. Med.* **15**, 27–37 (2010).
51. Matthews, T., Lo, A. Y. & Byrne, J. A. Reconceptualizing green infrastructure for climate change adaptation: barriers to adoption and drivers for uptake by spatial planners. *Landsc. Urban Plan.* **138**, 155–163 (2015).
52. Poustie, M. S. & Deletic, A. Modeling integrated urban water systems in developing countries: case study of Port Vila, Vanuatu. *Ambio* **43**, 1093–1111 (2014).
53. Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B. & Maurer, M. Emerging solutions to the water challenges of an urbanizing world. *Science* **352**, 928–933 (2016).
54. Poustie, M. S. et al. Sustainable urban water futures in developing countries: the centralised, decentralised or hybrid dilemma. *Urban Water J.* **12**, 543–558 (2015).
55. Lawrence, A., De Vreese, R., Johnston, M., Konijnendijk van den Bosch, C. C. & Sanesi, G. Urban forest governance: towards a framework for comparing approaches. *Urban For. Urban Green.* **12**, 464–473 (2013).
56. Cutter, S. L., Boruff, B. J. & Shirley, W. L. Social vulnerability to environmental hazards. *Soc. Sci. Q.* **84**, 242–261 (2003).
57. Paul, B. K. Factors affecting evacuation behavior: the case of 2007 Cyclone Sidr, Bangladesh. *Prof. Geogr.* **64**, 401–414 (2012).
58. O'Neill, M. S., Zanobetti, A. & Schwartz, J. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *J. Urban Health* **82**, 191–197 (2005).
59. Flocks, J., Escobedo, F., Wade, J., Varela, S. & Wald, C. Environmental justice implications of urban tree cover in Miami-Dade County, Florida. *Environ. Justice* **4**, 125–134 (2011).
60. Nowak, D. J., Crane, D. E. & Stevens, J. C. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* **4**, 115–123 (2006).
61. Janhäll, S. Review on urban vegetation and particle air pollution — deposition and dispersion. *Atmos. Environ.* **105**, 130–137 (2015).
62. McPherson, E. G. & Kendall, A. A life cycle carbon dioxide inventory of the Million Trees Los Angeles program. *Int. J. Life Cycle Assess.* **19**, 1653–1665 (2014).
63. Hamstead, Z. A., Kremer, P., Larondelle, N., McPhearson, T. & Haase, D. Classification of the heterogeneous structure of urban landscapes (STURLA) as an indicator of landscape function applied to surface temperature in New York City. *Ecol. Indic.* **70**, 574–585 (2016).
64. Pinsky, M. L., Guannel, G. & Arkema, K. K. Quantifying wave attenuation to inform coastal habitat conservation. *Ecosphere* **4**, 1–16 (2013).
65. Xiao, Q. & McPherson, E. G. Surface water storage capacity of twenty tree species in Davis, California. *J. Environ. Qual.* **45**, 188 (2016).
66. Berland, A. et al. The role of trees in urban stormwater management. *Landsc. Urban Plan.* **162**, 167–177 (2017).
67. Badami, M. G. & Ramankutty, N. Urban agriculture and food security: a critique based on an assessment of urban land constraints. *Glob. Food Sec.* **4**, 8–15 (2015).
68. Gunawardena, K. R., Wells, M. J. & Kershaw, T. Utilising green and bluespace to mitigate urban heat island intensity. *Sci. Total Environ.* **584–585**, 1040–1055 (2017).
69. Zardo, L., Geneletti, D., Pérez-Soba, M. & Van Eupen, M. Estimating the cooling capacity of green infrastructures to support urban planning. *Ecosyst. Serv.* **26**, 225–235 (2017).
70. Narayan, S. et al. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE* **11**, e0154735 (2016).
71. Koch, E. W. et al. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. *Front. Ecol. Environ.* **7**, 29–37 (2009).
72. National Research Council *Mitigating Shore Erosion Along Sheltered Coasts* (The National Academies Press, Washington DC, 2007).
73. Guswa, A. J., Hamel, P. & Dennedy-Frank, P. J. Potential effects of landscape change on water supplies in the presence of reservoir storage. *Water Resour. Res.* **53**, 2679–2692 (2017).
74. Hamel, P., Daly, E. & Fletcher, T. D. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: a review. *J. Hydrol.* **485**, 201–211 (2013).
75. Palliwoda, J., Kowarik, I. & von der Lippe, M. Human–biodiversity interactions in urban parks: the species level matters. *Landsc. Urban Plan.* **157**, 394–406 (2017).
76. Qiu, L., Lindberg, S. & Nielsen, A. B. Is biodiversity attractive? On-site perception of recreational and biodiversity values in urban green space. *Landsc. Urban Plan.* **119**, 136–146 (2013).
77. Barnes, M. et al. Characterizing nature and participant experience in studies of nature exposure for mental health, an integrative review. *Front. Psychol.* (in the press).
78. Nagendra, H., Bai, X., Brondizio, E. S. & Lwasa, S. The urban south and the predicament of global sustainability. *Nat. Sustain.* **1**, 341–349 (2018).
79. Fletcher, T. D., Andrieu, H. & Hamel, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Adv. Water Resour.* **51**, 261–279 (2013).
80. Walsh, C. J. et al. Principles for urban stormwater management to protect stream ecosystems. *Freshw. Sci.* **35**, 398–411 (2016).
81. Cohen, D. A. et al. The prevalence and use of walking loops in neighborhood parks: a national study. *Environ. Health Perspect.* **125**, 170–174 (2017).
82. Ramsay, G. et al. The barriers to millennials visiting Rouge Urban National Park. *Sustainability* **9**, 904 (2017).
83. Kondolf, G. M. & Pinto, P. J. The social connectivity of urban rivers. *Geomorphology* **277**, 182–196 (2017).
84. McCormack, G. R., Rock, M., Toohey, A. M. & Hignell, D. Characteristics of urban parks associated with park use and physical activity: a review of qualitative research. *Health Place* **16**, 712–726 (2010).
85. IPCC *Climate Change 2014: Synthesis Report* (eds Core Writing Team, Pachauri, R. K. & Meyer L. A.) (IPCC, 2014).
86. Vos, P. E. J., Maiheu, B., Vankerkom, J. & Janssen, S. Improving local air quality in cities: to tree or not to tree? *Environ. Pollut.* **183**, 113–122 (2013).
87. Paerl, H. W. & Huisman, J. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environ. Microbiol. Rep.* **1**, 27–37 (2009).
88. Nowak, D. J., Stevens, J. C., Sisinni, S. M. & Luley, C. J. Effects of urban tree management and species selection on atmospheric carbon dioxide. *J. Arboric.* **28**, 113–122 (2002).
89. Andrade, L. H. et al. Mental disorders in megacities: findings from the São Paulo Megacity Mental Health Survey, Brazil. *PLoS ONE* **7**, e31879 (2012).
90. Bratman, G. N., Hamilton, J. P., Hahn, K. S., Daily, G. C. & Gross, J. J. Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proc. Natl Acad. Sci. USA* **112**, 8567–8572 (2015).
91. Kuehler, E., Hathaway, J. & Tirpak, A. Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network. *Ecohydrology* **10**, e1813 (2017).
92. Criss, R. E. Statistics of evolving populations and their relevance to flood risk. *J. Earth Sci.* **27**, 2–8 (2016).
93. de Risi, R. et al. Flood risk assessment for informal settlements. *Nat. Hazards* **69**, 1003–1032 (2013).
94. Apparicio, P. & Séguin, A.-M. Accessibility of services and facilities for elderly residents of public housing in Montreal: an equity issue. *Urban Stud.* **43**, 187–211 (2006).
95. Rigolon, A. A complex landscape of inequity in access to urban parks: a literature review. *Landsc. Urban Plan.* **153**, 160–169 (2016).
96. Arkema, K. K. et al. Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Change* **3**, 913–918 (2013).
97. Loughnan, M., Nicholls, N. & Tapper, N. J. Mapping heat health risks in urban areas. *Int. J. Popul. Res.* **2012**, 1–12 (2012).
98. Wolch, J. R., Byrne, J. & Newell, J. P. Urban green space, public health, and environmental justice: the challenge of making cities 'just green enough'. *Landsc. Urban Plan.* **125**, 234–244 (2014).
99. Kwon, Y., Joo, S., Han, S. & Park, C. Mapping the distribution pattern of gentrification near urban parks in the case of Gyeongui Line Forest Park, Seoul, Korea. *Sustainability* **9**, 231 (2017).
100. Anguelovski, I., Connolly, J. J. T., Masip, L. & Pearsall, H. Assessing green gentrification in historically disenfranchised neighborhoods: a longitudinal and spatial analysis of Barcelona. *Urban Geogr.* **3**, 1–34 (2018).
101. Nagendra, H. & Ostrom, E. Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore, India. *Ecol. Soc.* **19**, 67 (2014).
102. Unnikrishnan, H. & Nagendra, H. Privatizing the commons: impact on ecosystem services in Bangalore's lakes. *Urban Ecosyst.* **18**, 613–632 (2015).

103. Klinenberg, E. *Heat Wave: A Social Autopsy of Disaster in Chicago* (Univ. Chicago Press, Chicago, 2003).
104. Klein Rosenthal, J., Kinney, P. L. & Metzger, K. B. Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health Place* **30**, 45–60 (2014).
105. Bedimo-Rung, A. L., Mowen, A. J. & Cohen, D. A. The significance of parks to physical activity and public health. *Am. J. Prev. Med.* **28**, 159–168 (2005).
106. Pham, T. T. H., Apparicio, P., Séguin, A. M., Landry, S. & Gagnon, M. Spatial distribution of vegetation in Montreal: an uneven distribution or environmental inequity? *Landsc. Urban Plan.* **107**, 214–224 (2012).
107. Crawford, D. et al. Do features of public open spaces vary according to neighbourhood socio-economic status? *Health Place* **14**, 887–891 (2008).
108. Cameron, R. et al. The domestic garden — its contribution to urban green infrastructure. *Urban For. Urban Green.* **11**, 129–137 (2012).
109. Kortright, R. & Wakefield, S. Edible backyards: a qualitative study of household food growing and its contributions to food security. *Agric. Hum. Values* **28**, 39–53 (2011).
110. Mitchell, R. & Popham, F. Effect of exposure to natural environment on health inequalities: an observational population study. *Lancet* **372**, 1655–1660 (2008).
111. Wheeler, B. W. et al. Beyond greenspace: an ecological study of population general health and indicators of natural environment type and quality. *Int. J. Health Geogr.* **14**, 1–17 (2015).
112. Andersson, E., Tengö, M., McPhearson, T. & Kremer, P. Cultural ecosystem services as a gateway for improving urban sustainability. *Ecosyst. Serv.* **12**, 165–168 (2015).
113. Vollmer, D. & Grêt-Regamey, A. Rivers as municipal infrastructure: demand for environmental services in informal settlements along an Indonesian river. *Glob. Environ. Change.* **23**, 1542–1555 (2013).
114. Poe, M. R., McLain, R. J., Emery, M. & Hurley, P. T. Urban forest justice and the rights to wild foods, medicines, and materials in the city. *Hum. Ecol.* **41**, 409–422 (2013).
115. Roy, S., Byrne, J. & Pickering, C. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Green.* **11**, 351–363 (2012).
116. Lin, B. B. et al. Local- and landscape-scale land cover affects microclimate and water use in urban gardens. *Sci. Total Environ.* **610–611**, 570–575 (2018).
117. Vico, G., Revelli, R. & Porporato, A. Ecohydrology of street trees: design and irrigation requirements for sustainable water use. *Ecohydrology* **7**, 508–523 (2014).
118. Litvak, E., Manago, K. F., Hogue, T. S. & Pataki, D. E. Evapotranspiration of urban landscapes in Los Angeles, California at the municipal scale. *Water Resour. Res.* **53**, 4236–4252 (2017).
119. Janke, B. D., Finlay, J. C. & Hobbie, S. E. Trees and streets as drivers of urban stormwater nutrient pollution. *Environ. Sci. Technol.* **51**, 9569–9579 (2017).
120. Churkina, G. et al. Effect of VOC emissions from vegetation on air quality in Berlin during a heatwave. *Environ. Sci. Technol.* **51**, 6120–6130 (2017).
121. Hobbie, S. E. et al. Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. *Proc. Natl Acad. Sci. USA* **114**, 4177–4182 (2017).
122. Booth, D. B., Roy, A. H., Smith, B. & Capps, K. Global perspectives on the urban stream syndrome. *J. Freshw. Sci.* **35**, 412–420 (2016).
123. Tallis, M., Taylor, G., Sinnett, D. & Freer-Smith, P. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landsc. Urban Plan.* **103**, 129–138 (2011).
124. McDonald, R. et al. *Planting Healthy Air: a Global Analysis of the Role of Urban Trees in Addressing Particulate Matter Pollution and Extreme Heat* (The Nature Conservancy, 2016).
125. Mcpherson, E. G., Kendall, A. & Albers, S. Million Trees Los Angeles: carbon dioxide sink or source? In *Proc. Urban Trees Research Conference* (eds Johnston, M. & Perceival, G.) 7–19 (2014).
126. Hardy, D., Cubillo, F., Han, M. & Li, H. *Alternative Water Resources: A Review of Concepts, Solutions and Experiences* (Alternative Water Resources Cluster International Water Association, 2015).
127. Dadson, S. J. et al. A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proc. R. Soc. A* **473**, 20160706 (2017).
128. Depietri, Y., Renaud, F. G. & Kallis, G. Heat waves and floods in urban areas: a policy-oriented review of ecosystem services. *Sustain. Sci.* **7**, 95–107 (2012).
129. CoDyre, M., Fraser, E. D. G. & Landman, K. How does your garden grow? An empirical evaluation of the costs and potential of urban gardening. *Urban For. Urban Green.* **14**, 72–79 (2015).
130. Martellozzo, F. et al. Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand. *Environ. Res. Lett.* **9**, 064025 (2014).
131. Kaplan, S. The restorative benefits of nature: toward an integrative framework. *J. Environ. Psychol.* **15**, 169–182 (1995).
132. Bolund, P. & Hunhammar, S. Ecosystem services in urban areas. *Ecol. Econ.* **29**, 293–301 (1999).
133. Rall, E., Bieling, C., Zytynska, S. & Haase, D. Exploring city-wide patterns of cultural ecosystem service perceptions and use. *Ecol. Indic.* **77**, 80–95 (2017).
134. Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L. & Smith, L. A. Overcoming uncertainty and barriers to adoption of blue-green infrastructure for urban flood risk management. *J. Flood Risk Manag.* **11**, S960–S972 (2018).
135. Sampson, R. J. Urban sustainability in an age of enduring inequalities: advancing theory and ecometrics for the 21st-century city. *Proc. Natl Acad. Sci. USA* **114**, 8957–8962 (2017).
136. Ernstson, H. The social production of ecosystem services: a framework for studying environmental justice and ecological complexity in urbanized landscapes. *Landsc. Urban Plan.* **109**, 7–17 (2013).
137. Díaz, S. et al. Assessing nature's contributions to people. *Science.* **359**, 270–272 (2018).
138. Jenerette, G. D. Ecological contributions to human health in cities. *Landsc. Ecol.* **33**, 1655–1668 (2018).
139. Trimmer, J. T. & Guest, J. S. Recirculation of human-derived nutrients from cities to agriculture across six continents. *Nat. Sustain.* **1**, 427–435 (2018).
140. Seto, K. C., Güneralp, B. & Hutyra, L. R. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl Acad. Sci. USA* **109**, 16083–16088 (2012).
141. Roy, A. Urban informality: toward an epistemology of planning. *J. Am. Plan. Assoc.* **71**, 147–158 (2005).

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Competing interests

The authors declare no competing interests.

Additional information

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