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# Toward Zero-Carbon Urban Transitions with Health, Climate Resilience, and Equity Co-Benefits: Assessing Nexus Linkages

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## Keywords

decarbonization, health, well-being, equity, resilience, urban metabolism, sustainable development goals, SDGs

## Abstract

Getting to net-zero-carbon cities while advancing well-being (W), health (H), social equity (E), and climate resilience (R) (referred to as the WHER outcomes) is critical for local and global sustainability. However, science is nascent on the linkages between zero-carbon pathways and WHER outcomes. This article presents a transboundary urban metabolism framework, rooted in seven key infrastructure and food provisioning systems, to connect urban decarbonization strategies with WHER outcomes. Applying the framework along with a literature review, we find the evidence for co-beneficial decarbonization to be strong for health; limited for well-being; uncertain for resilience; and requiring intentional design to advance equity, including distributional, procedural, and recognitional aspects. We describe the evidence base, identify key knowledge gaps, and delineate broad parameters of a new urban nexus science to enable zero-carbon urban transitions with WHER co-benefits. We highlight the need for fine-scale data encompassing all seven sectors across scales, along with multiple and multiscale climate risks, accompanied by next-generation multisector, multiscale, multioutcome nexus models.

## Contents

## 1. INTRODUCTION AND RATIONALE

Urban areas are centers of human productivity and ingenuity, housing >56% of the world population today and generating more than 80% of the world's gross domestic product (1). With the urban population share expected to increase to 68% by 2050 (2), urban areas are increasingly being recognized as a key action arena for global carbon mitigation, while also advancing multiple sustainable development goals (SDGs) locally related to human well-being (W), health (H), social equity (E), and climate resilience (R) (3, 4), henceforth referred to as the WHER outcomes.

Although urbanization has been recognized as critical to national economic development (5), the benefits of urbanization—in terms of gains in economy, health, and well-being—have not been realized to their full extent (6). For example, social inequality is high in many developing world cities where >30% of the population often lives in informal settlements lacking basic infrastructure, such as piped water, electricity, sanitation, and structurally safe housing (6). Many urban residents in cities worldwide are disproportionately exposed to high pollution levels, particularly fine particulate matter ($PM_{2.5}$) in the air, resulting from the burning of fossil fuel in energy, mobility, and construction sectors (7, 8), and burning of municipal solid waste (9). Unequal exposure to air pollution and poor access to nutritious food and active mobility contribute to unequal health outcomes, e.g., lifespan disparities exceeding 15 years between adjacent neighborhoods in some US cities (10, 11). Climate stressors such as extreme heat, flooding, hurricanes, and wildfires (see

## GLOBAL IMPACT OF INFRASTRUCTURE AND FOOD PROVISIONING SYSTEMS ON GREENHOUSE GAS EMISSIONS, SOCIAL INEQUALITY, HEALTH, AND CLIMATE RISKS

**Greenhouse Gas (GHG) Emissions:** The seven key infrastructure provisioning systems contribute ~90% of the global GHG emissions (20; see also **Figure 5**).

**Inequality:** Social inequality in cities, e.g., by income, race, caste, and other factors, physically manifests in the form of high levels of infrastructure inequalities, specifically, slums/informal settlements that lack sanitation, structurally safe housing, water supply, electricity, and clean energy supply. Globally, >1 billion people live in slums, primarily in cities in Asia and Africa (53), where the proportion of slum dwellers can range from 20%–60% (54). In the United States, a high-income country that is experiencing high levels of homelessness, >600,000 (approximately 0.2% of US population) and >930,000 urban residents (approximately 0.35% of US urban population) lack access to piped water and sanitation, respectively (55). The marginalized and poor in cities worldwide also face disproportionately high exposure to climate and health risks and reduced access to health care.

**Health:** Health risks worldwide arising from inadequate, unequal, and polluting infrastructure systems contributed to ~19 million premature deaths in 2019 (56, 57; see also **Figure 5**). The top three risk factors are air pollution associated with the energy systems, poor nutrition associated with the food system, and accidents and reduced physical activity linked to mobility systems (see **Figure 5**) (58). Globally, disaster-related mortality was ~15,000 (59). Additional urban-specific health risks include noise (60) and heat stress (61), as well as reduced access to greenery and parks that affect well-being (62).

**Multiple Urban Climate Risks:** Urban areas and infrastructure are subject to diverse climate risks, including the following:

> Urban heat: By 2050, 1.6 billion people in 970 cities will be exposed to extreme heat (63). Average urban temperatures changed over the past century from 1 to 7°C across 26 global cities (64), with cities in temperate latitudes seeing the largest changes (e.g., London), due to the urban heat island effect where temperatures can exceed surrounding hinterlands by as much as 4°C in some cities. Intracity differences can be as high as 15°C between shade and sun. Elevated temperatures, and in combination with high humidity, can cause heat stress, which prevents the human body from cooling down. Several indices exist that measure heat stress, accounting for temperature and humidity, including heat index and wet bulb globe temperature (63, 65).
>
> Sea-level rise: By 2050, more than 800 million people will be exposed to coastal flooding exceeding 0.5 meters. Urban exposure to flooding has increased fourfold from 1985 to 2018 (66).
>
> Hurricanes: Economic damages from storms (high wind, precipitation, and flooding) in 2022 exceeded $20 billion primarily in US urban areas (estimates based on 67) due to power outages and urban flooding following hurricanes as seen previously in hurricanes Harvey and Ida. Attribution to climate change is modest (54) while emerging research suggests tropical cyclones may be intensifying and moving to higher latitudes with potential to impact cities as far north as Boston (68).
>
> Wildfires: In the United States, one-third of all houses and one-tenth of land area at the wildland-urban interface is considered to be at risk of wildfires (69). In 2022, $0.2 billion in damages was attributed to wildfires and anticipatory power cuts (67).

the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks) are now impacting >1.4 billion people worldwide, including >400 million people concentrated in some of the world's largest cities (**Table 1**), disrupting lives, wreaking economic damage, and impacting public health unequally.

**Table 1** Top 20 global cities with the highest annual average air pollution concentrations (focused on particulate matter), heat index, and projected population exposed to coastal flooding, wherein net-zero pathways may enable mitigation of or resilience to such risks

| | Most polluted cities[a] | | | Cities with the highest heat index[b] | | | Cities with the highest population exposed to coastal flooding[c] | |
|---|---|---|---|---|---|---|---|---|
| Rank | City, country | Annual average $PM_{2.5}$ (μg/m$^3$) | Population (million)[d] | City, country | Heat index | 2020 Population (million)[d] | City, country | 2020 Population (million)[d] |
| 1 | Lahore, Pakistan | 108 | 12.6 | Chennai, India | 127 | 10.97 | Kolkata, India | 14.85 |
| 2 | Delhi, India | 91 | 30.3 | Ahvaz, Iran | 118 | 1.24 | Mumbai, India | 20.41 |
| 3 | Dhaka, Bangladesh | 85 | 21 | Bangkok, Thailand | 118 | 10.54 | Dhaka, Bangladesh | 21.01 |
| 4 | Ghaziabad, India | 85 | 1.9 | Ho Chi Minh, Vietnam | 116 | 8.60 | Guangzhou, China | 13.30 |
| 5 | Muzaffarnagar, India | 84 | 0.7 | Nanchang, China | 116 | 3.60 | Ho Chi Minh City, Vietnam | 8.60 |
| 6 | Peshawar, Pakistan | 84 | 2.2 | Fuzhou, China | 115 | 3.69 | Shanghai, China | 27.06 |
| 7 | Aguascalientes, Mexico | 80 | 1.1 | Hangzhou, China | 115 | 7.64 | Bangkok, Thailand | 10.54 |
| 8 | Hapur, India | 76 | 0.3 | Djibouti, Djibouti | 114 | 0.58 | Rangoon, Myanmar | 5.33 |
| 9 | Lucknow, India | 64 | 3.7 | Houston, Texas, USA | 113 | 6.37 | Miami, Florida, USA | 6.12 |
| 10 | Patna, India | 60 | 2.4 | San Antonio, Texas, USA | 113 | 2.32 | Hai Phòng, Vietnam | 1.30 |
| 11 | Dammam, Saudi Arabia | 53 | 1.2 | Guangzhou, China | 113 | 13.30 | Alexandria, Egypt | 5.28 |
| 12 | Ulan Bator, Mongolia | 52 | 1.6 | Changsha, China | 112 | 4.58 | Tianjin, China | 13.59 |
| 13 | Chandigarh, India | 51 | 1.15 | Austin, Texas, USA | 111 | 2.05 | Khulna, Bangladesh | 0.95 |
| 14 | Baghdad, Iraq | 48 | 7.2 | Phoenix, Arizona, USA | 110 | 4.51 | Ningbo, China | 4.12 |
| 15 | Jaipur, India | 48 | 3.9 | Timbuktu, Mali | 110 | 0.05 | Lagos, Nigeria | 14.37 |
| 16 | Kolkata, India | 48 | 14.9 | Nanning, China | 110 | 3.86 | Abidjan, Côte d'Ivoire | 6.32 |
| 17 | Kampala, Uganda | 48 | 3.3 | Cairo, Egypt | 109 | 20.90 | New York, NY/ Newark, New Jersey, USA | 18.80 |
| 18 | Urumqi, China | 47 | 4.1 | Chongquing, China | 109 | 15.87 | Chittagong, Bangladesh | 5.02 |
| 19 | Xinxiang, China | 47 | 1.1 | Dakar, Senegal | 109 | 3.14 | Tokyo, Japan | 37.39 |
| 20 | Manama, Bahrain | 47 | 0.6 | Jackson, Mississippi, USA | 108 | 0.42 | Jakarta, Indonesia | 10.77 |

[a] Data Source: Air Quality Open Data Platform from **https://aqicn.org/data-platform/covid19/**.

[b] Data Source: European Centre for Medium-Range Weather Forecasts (2021). Heat Index Equation (284).

[c] Data Source: Ranking of the world's cities most exposed to coastal flooding today and in the future (285).

[d] Data Source: United Nations, Department of Economic and Social Affairs, Population Division (286).

Against this backdrop, urban activities collectively contribute >70% of global greenhouse gas (GHG) emissions when accounting for fossil fuel and electricity imports to cities (12, 13). Scientists and policymakers are increasingly recognizing the importance of quantifying direct territorial (Scope 1) GHG emissions, as well as GHGs associated with transboundary supply of key provisioning systems, including imported electricity (Scope 2) and life cycle (Scope 3) emissions associated with producing fuels, food, and construction materials necessary for the functioning of homes and businesses in cities. Community-wide infrastructure and food supply chain footprints have been advanced in the scientific literature (14–17) and institutionalized in city-level GHG protocols such as ICLEI's US Community Protocol and the Global Protocol for Cities (18, 19) used by hundreds of cities worldwide. A focus on seven key provisioning systems that provide energy, mobility, shelter/building materials, food, water, waste management, and green infrastructure/public spaces is strategic because, globally, these sectors collectively contribute >90% of global GHG emissions (16, 20). Furthermore, these provisioning systems foundationally impact WHER outcomes in cities (16). Thus, a focus on provisioning systems enables cities to chart pathways to low-carbon and zero-carbon goals with WHER co-benefits.

Since 1990, several hundreds of cities have committed to reducing GHG emissions through the US Mayors Climate Protection Agreement (**https://www.usmayors.org/programs/mayors-climate-protection-center/**), the Global Covenant of Mayors for Climate and Energy (**https://www.globalcovenantofmayors.org/**), and C-40 cities (21). In 2011, the United Nations Framework Convention on Climate Change formally recognized the importance of cities and infrastructure systems in GHG mitigation and climate adaptation. More recently, consistent with global efforts to achieve net-zero emissions by 2050 (22), more than 1,100 cities have adopted net-zero-carbon goals. A recent review article (23) distinguishes between urban low-carbon versus net-zero-carbon goals, noting that low-carbon strategies encompassing efficiency and conservation can never yield net-zero emissions, as they cannot "zero-out" the use of fossil fuels. In contrast, net-zero emission strategies that yield deep reductions in GHG emissions require systemic transitions in infrastructure and food systems anchored upon a zero-carbon electricity grid, accompanied by mobility and heating transitions to electricity and a range of carbon valorization and sequestration efforts across food-energy-water-waste (FEWW) and green infrastructure sectors. Henceforth, we use the term net-zero-carbon emissions, or simply zero-carbon as a simpler way of referring to net-zero GHG emissions.

Zero-carbon pathways have been delineated globally (24, 25) and at national scales for India (26), China (27), South Africa (28), and the United States (29, 30). The role of cities in achieving national and global zero-carbon outcomes has been less studied. Most city-scale zero-carbon models focus only on energy use in buildings and mobility (23), although recent studies are incorporating land use efficiency (31), integrated land use planning (32), urban industrial symbiosis (33), mass timber construction (34, 35), and nature-based solutions (36). More recently, emerging models are integrating multiple strategies across all seven provisioning systems to chart city-wide decarbonization (37). As the world and its urban areas undertake major investments to achieve zero-carbon goals by 2050, it is imperative that these zero-carbon transitions are designed to also advance WHER outcomes.

Many cities have already recognized the nexus between decarbonization and WHER outcomes; for example, New York City's goals connect the economy, social justice, sustainability, and resilience (38). ICLEI-USA, a network of 600 US cities, recently created a task force to develop metrics for decarbonization, equity, and climate resilience (**https://iclei.org/activity/accelerating-transitions-to-zero-carbon-sustainable-urban-mobility-systems/**). A policy statement from the American Heart Association is recognizing the nexus between health and various sustainability plans (39), as does the Planetary Health Alliance (40). However, there has been little systematic study of the mechanisms through which zero-carbon strategies can advance WHER outcomes, and the models/measurements that demonstrate these linkages.

This article presents a systems framework and associated literature review to evaluate the linkages between zero-carbon pathways in cities and multiple WHER outcomes. We do not address all pathways to creating climate-resilient, healthy, or equitable cities; rather, our focus is on zero pathways and their intersection with the multiple WHER outcomes.

Section 2 presents a conceptual framework anchored upon key provisioning systems that enables assessing pathways toward zero-carbon cities, with potential linkages to WHER outcomes. Sections 3–5 subsequently apply the framework to evaluate mechanisms by which urban zero-carbon strategies intersect with health and well-being outcomes, climate resilience, and equity, respectively. Section 6 provides a synthesis and directions for future research. We discuss these topics from a global perspective, focusing on examples from the United States and India, to provide developed and developing world perspectives.

## 2. A SYSTEMS FRAMEWORK ANCHORED UPON KEY PROVISIONING SYSTEMS

A robust body of literature over the past 10–15 years articulates physical provisioning systems as the connector between natural systems, planetary boundaries, and human well-being. For example, Ramaswami et al. (20) show that seven key provisions systems that provide food, energy, water, mobility, shelter/building materials, waste management, and green/public spaces together contribute more than 90% of global GHG emissions, greater than 98% of water withdrawals and a vast majority of premature mortality associated with infrastructure- and environment-related risk factors. Likewise, O'Neill et al. (41) articulate physical provisioning systems as the link between planetary boundaries and human outcomes of health, well-being, inequality, and democracy. The importance of infrastructure and food provisioning systems as an anchor that connects multiple SDGs has also been acknowledged by several researchers (10, 42–45) and policymakers (4, 46).

### 2.1. A Transboundary Urban Metabolism Framework and Nexus Outcomes

We build on this prior literature to depict a social-ecological-infrastructural systems framework (**Figure 1**) anchored upon the concept of urban metabolism that connects demand for the seven key provisioning systems in cities with their transboundary supply (20, 47), shaped by people (social actors) and institutions across spatial scales. The seven provisioning systems are associated with transboundary community-wide GHG footprints and social inequality as well as climate and health risks, thus providing a conceptual framework for the nexus linkages among GHG emission and WHER outcomes. The sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks summarizes the massive global implications of infrastructure and food provisioning systems on GHGs, social inequality, health effects, and climate risks. **Table 1** illustrates the magnitude of populations in just the top 20 cities exposed to high levels of air pollution (115 million), extreme heat (124 million), and sea level rise (245 million). Globally, one or more of these impacts are expected in 59% of cities, large and small, impacting 1.4 billion people in 2018 (48).

The framework in **Figure 1** provides a structure wherein the same infrastructure and food provisioning systems connected to decarbonization outcomes, i.e., GHG footprints and their mitigation, are also linked to inequality within and across city boundaries, as well as health and climate risks, which relate to resilience. The framework recognizes large social inequalities in access to basic infrastructure and nutritious food within cities and that essential energy, water, food, construction materials, and mobility services are supplied via transboundary power, water, energy, food, and freight networks. For example, in the context of inequality in cities, significant

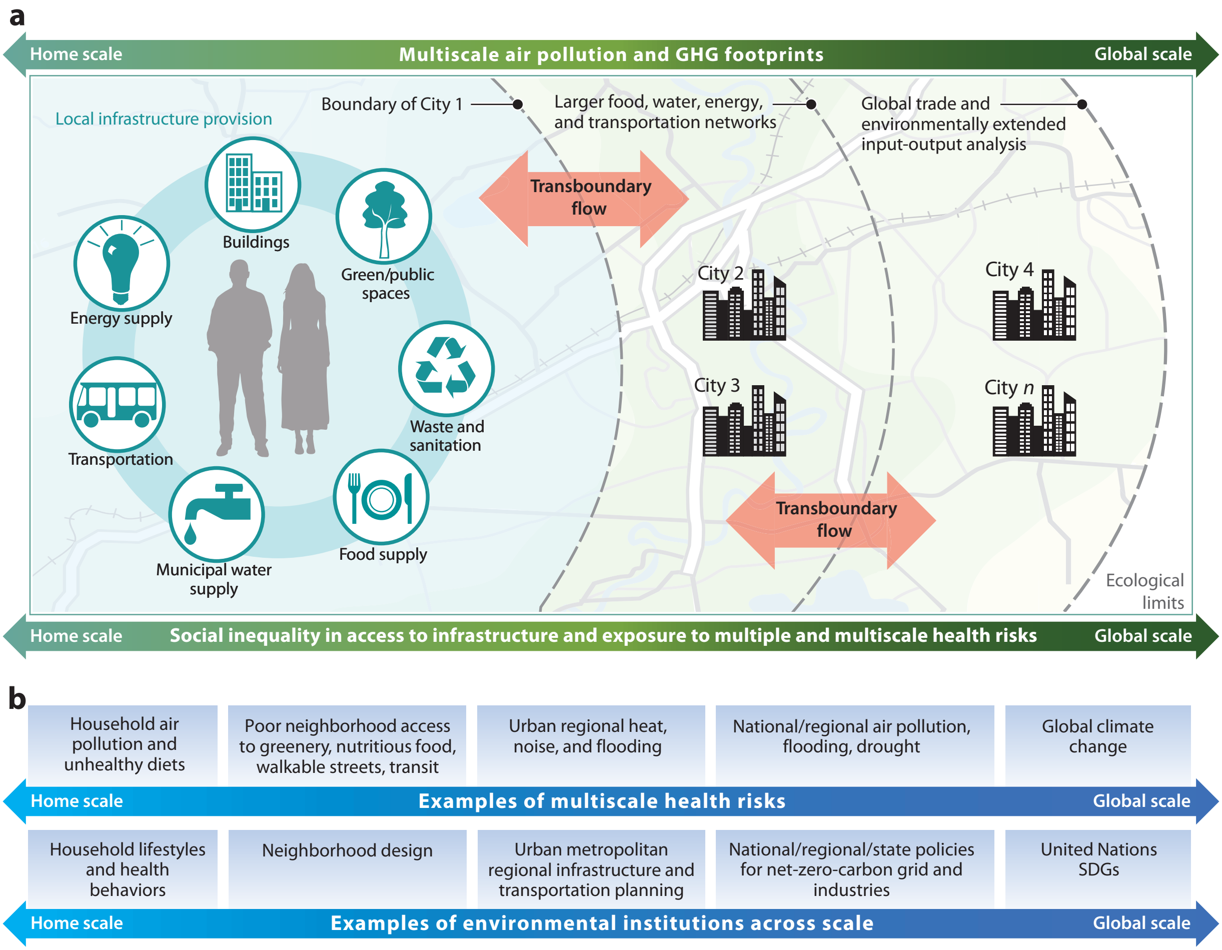


**Figure 1**

(*a*) Pictorial representation of various components of a social-ecological-infrastructural urban systems framework (adapted from References 20, 47). The framework anchors upon the concept of urban metabolism, illustrating the transboundary resource flows needed to support key physical provisioning systems within a city (*dashed line labeled Boundary of City 1*). The transboundary resource flows result in transboundary GHG, air pollution and natural resource/material footprints of the physical provisioning systems (*illustrated in the top green arrow*), associated with their local- to global-scale supply chain. The green arrow at the bottom of panel *a* illustrates social inequality in access to provisioning systems within the city, as well as exposure to multiple and multiscale health risks illustrated in panel *b*. (*b*) The top blue arrow provides examples of multiscale health risks arising from poor access to infrastructure and exposure to pollution and to climate-related risks. The bottom blue arrow illustrates that access and consumption of the provisioning systems, and exposure to associated risks, are shaped by institutions from household to global scales. Institutions refers to formal and informal norms that shape the behavior of social actors, including individuals, businesses, policy actors, etc. Adapted and expanded upon with permission from References 20, 47. Abbreviations: GHG; greenhouse gas, SDGs; sustainable development goals.

populations in Delhi, India, lack access to piped water (>25%), toilets (11%), sewerage (>41%), and permanent housing (12%) (49), and there are large intraurban differences in access to greenery and exposure to air pollution, noise, and heat stress (50). At the same time, food travels 418 km to reach Delhi (51), and electricity, food, and freight travel more than 320 km, 1930 km, and 960 km, respectively, in the United States (47). Correspondingly, health and climate risks are multi-scaled (**Figure 1*b***), including, at the household scale, indoor air pollution from biomass cooking stoves, lack of water and sanitation, and unhealthy diets; at the neighborhood scale, lack

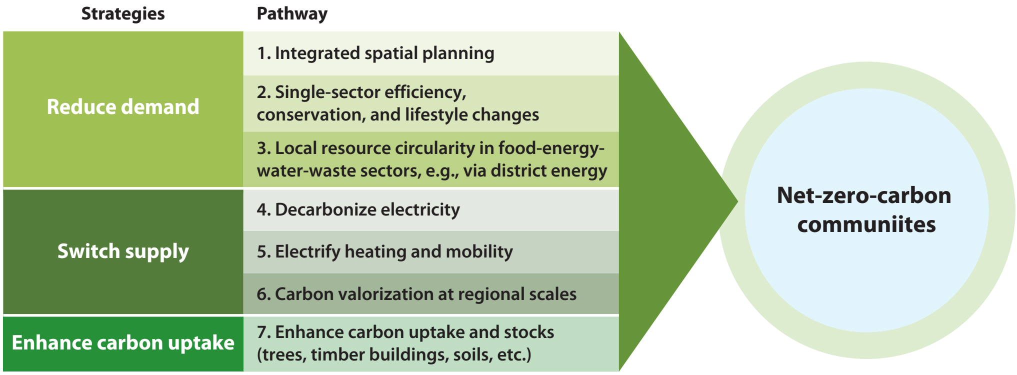


**Figure 2**

A schematic illustrating a sequence of three broad strategies encompassing seven pathways toward zero-carbon communities. Adapted from Reference 23.

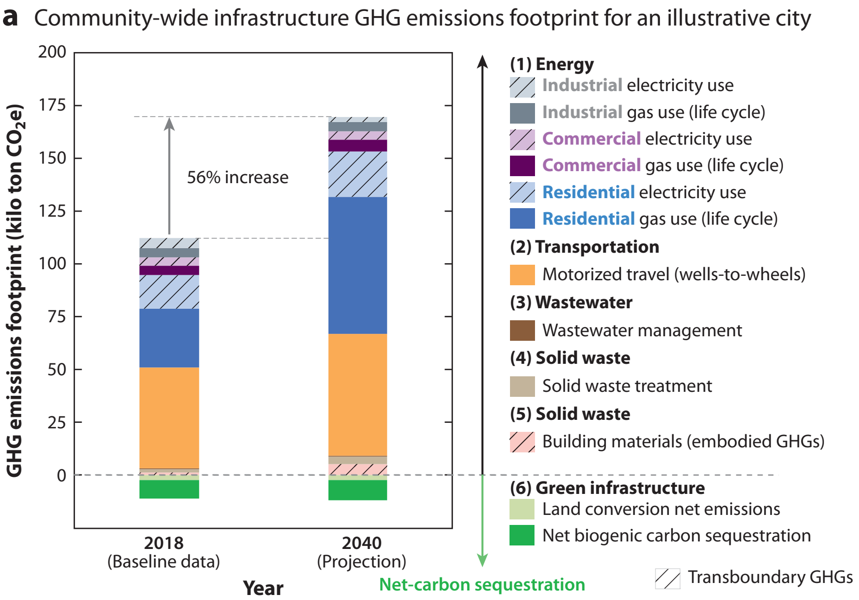
of access to greenery/trees, which can mitigate urban heat, nutritious food (food deserts), and walkable-bikeable streets that facilitate active lifestyles; and, at the urban-regional scale, local and regional flooding, urban heat island, air pollution, hurricanes, and drought. Some of these climate-related risk factors have been attributed to global climate change with varying levels of certainty, e.g., very likely for heat stress and likely for hurricanes (52). Extreme climate events (wind, flooding, etc.) can also disrupt urban food, water, and power networks, with secondary impacts on health, particularly during compounded events, i.e., heat stress following hurricane-related power outages. Systematically characterizing in- and transboundary infrastructure and food supply chains from a multi-outcome perspective enables addressing simultaneously GHG mitigation, health, well-being, inequality and climate resilience, and equity. We apply the seven-sector transboundary framework in **Figure 1** to first delineate urban zero-carbon pathways (see Section 2.2 and **Figure 2**) and then evaluate the nexus linkages between zero-carbon strategies and the outcomes of health and well-being, climate resilience, and equity.

## 2.2. Applying the Framework to Quantify Zero-Carbon Transition Strategies

The following two sections delineate two steps through which the urban metabolism framework can be applied to quantify the impact of zero-carbon transition strategies.

**2.2.1. Baseline greenhouse gas emission footprints.** Decarbonizing urban infrastructure and food provisioning systems will first require understanding the GHG emissions associated with urban provisioning systems. A community-wide transboundary infrastructure supply chain GHG footprint illustrated for a city in Minnesota, USA (see **Figure 3*a***) shows baseline (year 2018) direct and embodied GHGs associated with providing electricity and gas for buildings, petro fuels for mobility, construction materials, food, and water. Studies of numerous global cities (14, 17, 70–72) have shown that while the sectoral contributions can vary across cities, energy use in buildings and mobility tend to be dominant, followed by embodied emissions associated with food and construction materials, followed by water supply and waste, while greenery may result in a carbon sink (73). The relative contribution depends on the boundary and scope of emission accounting (74, 75).

**2.2.2. Pathways and strategies for urban decarbonization.** A recent consensus article among researchers and policymakers makes the case for defining a zero-carbon city as one with transboundary zero-carbon infrastructure and food provisioning systems (16), recognizing that globally these sectors contribute to >90% of global GHG emissions and also foundationally



**b** Features of illustrative city

| | 2018 | 2040 |
|---|---|---|
| Population | 10,428 | 22,300 |
| Household square foot/person | 763 | 825 |
| Household EUI (kBtu/square foot) | 71.8 | 68.1 |
| VMT/person/day | 32.8 | 22.8 |
| Gross population density (people/ha) | 1.83 | 3.91 |

**Figure 3**

Community-wide greenhouse gas (GHG) footprint for an illustrative city in Minnesota, USA, showing business-as-usual trends from 2018 to 2040. Panel *a* shows the community-wide infrastructure GHG emissions footprint, including six sectors: (*1*) Energy use and supply, shown in shades of blue, gray, and magenta to separate out gas and electricity (*hatched*), disaggregated by residential, commercial, and industrial; (*2*) mobility, shown in orange, including wells-to-wheels GHG emissions (tailpipe and petroleum refinery); (*3*) wastewater treatment, shown in dark brown; (*4*) solid waste management, shown in light brown; and (*5*) building materials, shown in hatched red. (*6*) Green infrastructure results in net-carbon sequestration, shown in green, as negative emissions. Panel *b* explains the context for changes in 2040, including population increase in living square footage, baseline improvements in energy use intensity (EUI), and vehicle miles traveled (VMT per person per day), largely due to greater densification and existing compact city plans.

impact inequality and health (20, 41, 45). These seven key provisioning systems, i.e., energy, mobility, transportation, construction, food systems, water, and wastewater, are also foundational to national decarbonization plans. Furthermore, when these pillar sectors decarbonize, almost all the other sectors of the economy will also decarbonize. Thus, defining a zero-carbon city as one with zero-carbon transboundary infrastructure and food systems, a recent review article delineates broad pathways and strategies for urban zero-carbon transitions (see **Figure 2** and Reference 23) in a manner consistent with and complementary to national decarbonization plans. The framework draws on multiple literatures, including the potential to achieve a factor of ten (i.e., 10x) resource efficiency through integrated spatial planning (32); single-sector efficiencies, particularly in buildings and mobility sectors that can reduce demand for energy and materials (76–78); meeting the remaining demand through fuel switching to electric heat pumps and electric vehicles (EVs) anchored upon a decarbonized grid (30, 79); followed by opportunities for carbon valorization (80) of biogenic "waste" carbon to renewable natural gas and other feedstocks; and, finally, carbon sequestration by urban trees (36, 81), mass timber construction (34), and constructed wetlands.

Reference 23 describes in detail the urban zero-carbon pathways and strategies. In this article, we organize the zero-carbon (ZEC) strategies into five categories to enable systematic linkages of these strategies with WHER outcomes in subsequent sections: ZEC Strategy #1: Integrated urban spatial planning; ZEC Strategy #2: Single-sector efficiency improvements to reduce demand (particularly focused on the dominant buildings and mobility sectors); ZEC Strategy #3: Fuel switching to electric heating and mobility, with decarbonized electricity supply; ZEC Strategy #4:

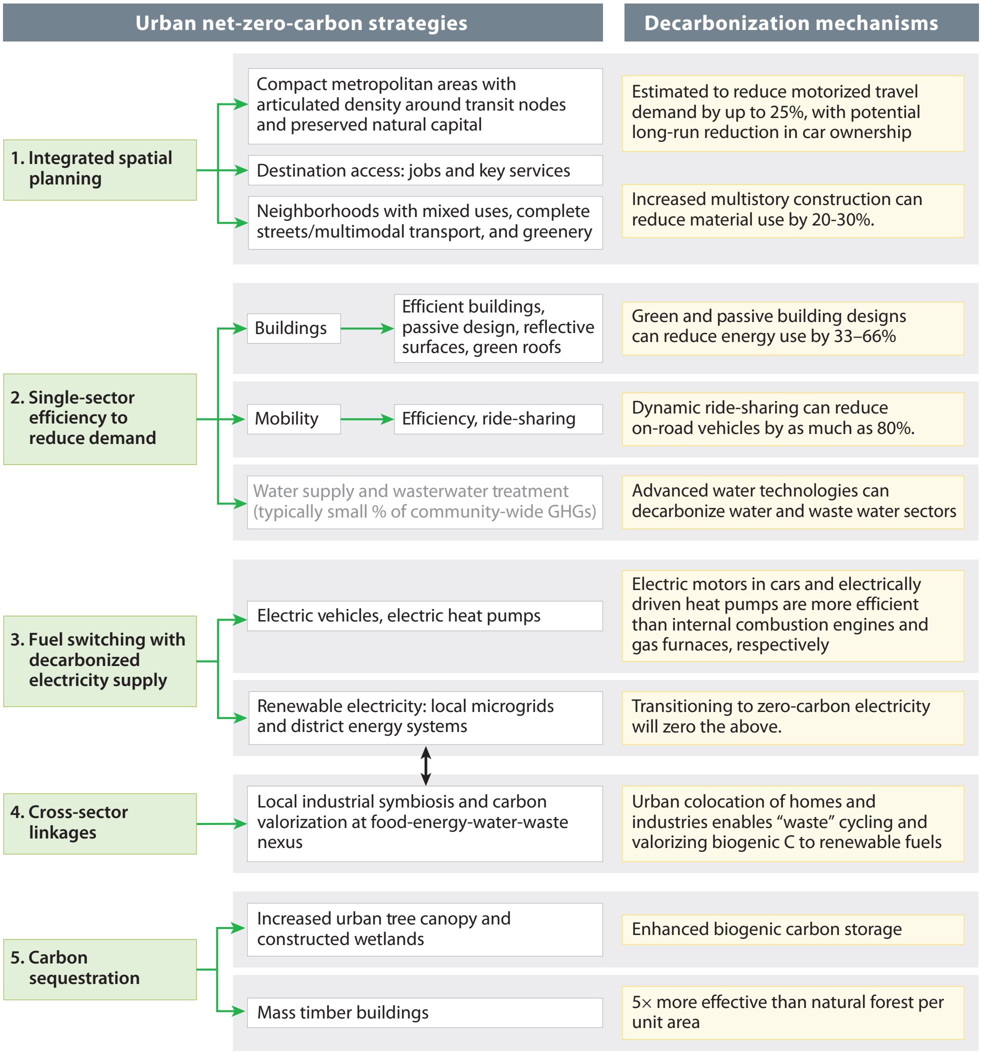


**Figure 4**

Schematic illustrating the nexus linkages between the broad decarbonization strategies and examples of typical specific actions (*left two columns; linkages shown in green arrows*), and potential decarbonization mechanisms (*right column*). Grayed out text indicates water supply and wastewater treatment sectors that have relatively small GHG contributions due to which associated strategies are not reviewed in this paper.

Cross-sector linkages, enabling urban industrial symbiosis and carbon valorization at the food-energy-water nexus; ZEC Strategy #5: Carbon sequestration including tree canopy, mass timber, and constructed wetlands. **Figure 4** illustrates how these strategies can contribute to decarbonization, the evidence base for which is detailed in Reference 23. A brief overview is therefore provided below, highlighting key mechanisms in **Figure 4**.

- **ZEC Strategy #1: Integrated urban spatial planning**. Integrated spatial planning involves addressing the “5 Ds”—density, diversity, neighborhood design, destination access (primarily to jobs), and distance (proximity) to transit—doubling all of which can yield up to a 25% reduction in motorized travel demand (82). Functionally, integrated spatial planning is implemented at three scales: (i) metropolitan regional scale design through a balanced spatial distribution of homes, jobs, and essential services between central cities and suburbs; (ii) mesoscale design with articulated density around transit nodes; and (iii) neighborhood-scale design with mixed residential-commercial use and multimodal streets enabling equitable access to parks, green spaces, and opportunity for active mobility through walkable and bikeable streets. These three tiers of implementation are expected to result in compact cities with reduced motorized vehicle travel and material requirements for buildings and infrastructures (32, 83–85), as well as improved and equitable access to transit, jobs and essential services, and neighborhood-level greenery and active lifestyles.

- **ZEC Strategy #2: Single-sector efficiency improvements to reduce demand.** Energy-efficient buildings (78) and behavioral nudging with smart meters can yield substantial reduction in energy use. Furthermore, new technologies such as dynamic ride-sharing (86) can reduce vehicles on the road by as much as 80%, based on microsimulations.
- **ZEC Strategy #3: Fuel switching to electric heating and mobility, with decarbonized electricity supply.** Transitioning heating to electric heat pumps, and fossil fuel–based mobility to EVs, in tandem with decarbonizing the power grid at both local and national scales can eliminate fossil fuel use for these services (30).
- **ZEC Strategy #4: Cross-sector linkages enabling symbiosis and carbon valorization.** Urban-industrial symbiosis (33, 87) involves exchange of waste heat and materials among industries, as well as between industry and proximal human settlements, which can create colocation efficiencies reducing fossil fuel use and virgin material extraction. Carbon valorization (80) entails upgrading waste biogenic carbon in wastewater and food water to renewable fuels and materials. Both strategies have potential to contribute to decarbonization, complementing larger-scale carbon capture, storage, and utilization (88).
- **ZEC Strategy #5: Carbon sequestration.** In urban areas, carbon sequestration can be achieved through strategies such as increasing tree canopy (36, 81), mass timber construction (34), and constructed wetlands (89). Achieving attendant carbon storage and sequestration benefits will require planting/maintaining long-lived trees (90) as well as timber replacement via sustainable reforestation (34).

All these strategies together can contribute substantially to urban deep decarbonization (37), with mechanisms illustrated in **Figure 4**. The degree to which each strategy contributes to decarbonization can depend on the path dependency and stage of urbanization of cities. For example, land use planning can play a critical role in brand new and rapidly growing cities emerging in Asia and Africa; however, the impact of land use planning can be muted in slow-growing metropolitan cities in parts of Europe and the United States.

Using the decarbonization strategies in **Figure 4** as an anchor, subsequent sections of this article evaluate nexus linkages to the WHER outcomes. Each section begins with an overview providing definitions and metrics to measure the various WHER outcomes, followed by a synthesis of the available evidence base demonstrating their nexus with urban zero-carbon strategies.

## 3. HEALTH AND WELL-BEING CO-BENEFITS OF URBAN ZERO-CARBON TRANSITIONS

### 3.1. Defining and Measuring Health and Well-Being

The World Health Organization defines health as “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity” (91, p. 1). Given the breadth of this definition, this article focuses on objective measures of health, i.e., measures of disease burden such as premature mortality, lifespan, and morbidity, as well as subjective well-being (SWB) wherein populations are queried through surveys on subjective assessments of their own well-being.

**3.1.1. Objective measures of disease burden.** Disease burden is often measured directly in hospitals and by public health agencies in terms of the number of hospital admissions and premature deaths associated with certain diseases. Population-wide assessments linking disease burden with various risk factors have most widely been reported by the Global Burden of Disease studies, using epidemiological models to connect environmental, infrastructural, metabolic, and behavioral risk factors to estimates of disease burden globally (92), in different nations (93), and more recently at the city scale (94, 95). Disease burden, i.e., premature mortality (premature deaths per 100,000 population) or disability associated with various causes, such as respiratory disease, cardiovascular disease, diabetes, and cancer, is shaped substantially by social inequality that manifests in infrastructure deprivation and disproportionate exposure to environmental pollution (96), also referred to as the social determinants of health (97). Quantitative health risk modeling generally involves multiplying the severity of the risk factor or hazard (e.g., air pollution concentrations or levels of heat stress) with the population fraction exposed to that risk, along with a response factor derived from relative risk factors comparing health effects in exposed versus unexposed populations (98).

Globally, infrastructure- and environment-related risk factors associated with the seven provisioning sectors are estimated to contribute to one-quarter to one-fifth of global mortality (99). **Figure 5** shows major socioenvironmental risk factors at the global scale contributing to premature mortality (also summarized in the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks), which include indoor and outdoor air pollution primarily associated with fossil fuel combustion in energy and mobility sectors, inadequate/poor nutrition associated with the food system, accidents and sedentary lifestyles linked to mobility systems, inadequate water sanitation and handwashing, and mortality arising directly from natural disasters (20, 57, 99–101). At the

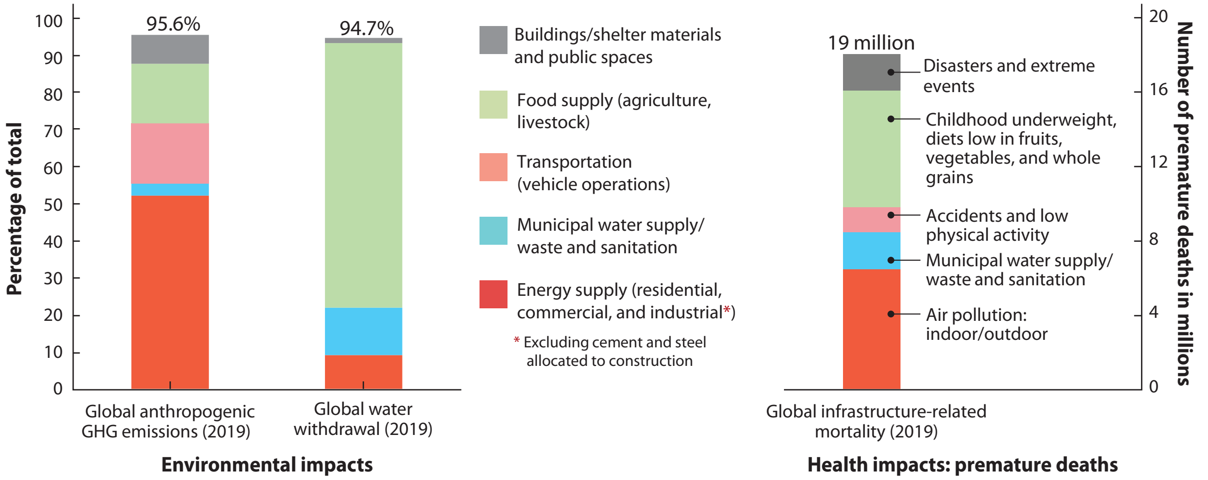


**Figure 5**

Global greenhouse gas (GHG) emissions and water withdrawal impacts (*left panel*), and global disease burden (*right panel*) for the year 2019 associated with seven infrastructure and food provisioning systems (noted in the *middle legend*). Figure adapted with permission from Reference 20. Data sources: GHG emissions (288–290), water withdrawal (291, 292), disease burden (293), and accident (294).

city level, additional risk factors may emerge as relevant, including noise pollution (above the 60-decibel level) (60, 94, 102, 103) and exposure to extreme heat events (61), both of which impact health by impairing sleep, exacerbating stress/inflammation and cardiovascular risk. Secondary mortality also occurs after storm and hurricane events (100), as well as from compounded risks from power loss during hurricanes followed by heat stress (104).

Lack of urban- and intraurban-scale data on these diverse risk factors is often a limiting factor in quantifying urban health risks. For example, publicly available data for a population of 21 million in Delhi include only 10 noise monitors, 2–3 weather stations, and 39 air pollution stations (94). Increasingly, fine-scale data on air pollution and extreme heat are being generated from a combination of field measurements, remote sensing, and modeling, further coupled with population census data to assess inequalities in exposure to ambient air pollution in cities (105–107), while community surveys on household behaviors inform behavioral risk factors (95). Overall, social, infrastructural and environmental-related health risk factors vary based on city types, geography, and level of development, with extremely high air pollution dominant in several developing cities (108). In contrast, in the United States, where air pollution levels have decreased substantially due to pollution control, unhealthy diets and physical inactivity, exacerbated by inadequate infrastructure in poor and racial minority neighborhoods, are leading risk factors (109, 110), highlighting the importance of equitable access to nutritious food and active mobility in cities.

In addition to the above noncommunicable diseases, COVID-19 has highlighted the importance of communicable diseases, particularly zoonotic diseases. In the United States, 1 in 8 deaths from 2020 to 2021 was attributed to COVID-19 (111), whereas in India 1 in 54 deaths was officially attributed to COVID-19 in 2020 (112). Infrastructure can be a risk factor for disease spread during pandemics, owing to mobility networks and overcrowding in enclosed environments (113, 114); however, population density per se is noted not to be as important as activity densities, i.e., gathering of people in schools, restaurants, and other indoor spaces (101, 115). Overall, social, infrastructural, environmental, behavioral, and mortality data availability at finer scales (116), alongside epidemiological models, are advancing the modeling of both communicable and noncommunicable disease burden in cities (60, 94, 117).

**3.1.2. Subjective well-being.** Scholars from different disciplines, e.g., public health, psychology, and economics, have highlighted the importance of complementing objective measures of population health (e.g., life span, premature mortality, or morbidity) and economic well-being (e.g., average income per capita) with subjective assessments that directly survey people on their well-being (118–120). The Centers for Disease Control and Prevention (109) define SWB as "judging life positively and feeling good." A large body of research has converged to recognize that SWB includes evaluative, emotional, and eudemonic dimensions, representing how we think (evaluative) and feel (emotional) about our lives, and contribute meaningfully (eudemonia). Survey instruments have accordingly become standardized with the United Kingdom's national census (see sidebar titled Examples of Survey Questions Evaluating Three Key Dimensions of Subjective Well-Being), and the US American Community Survey regularly queries respondents on their subjective well-being along these dimensions.

Consistently across the world, major correlates of SWB are found to be income, employment, physical health status, and age (121, 122). Unpacking the impacts of urban infrastructure and environment on SWB can therefore be challenging and requires careful study controlling for the major domain variables. We describe the evidence base emerging from these few studies as they relate to the well-being co-benefits of the zero-carbon transitions in Section 3.3.

## EXAMPLES OF SURVEY QUESTIONS EVALUATING THREE KEY DIMENSIONS OF SUBJECTIVE WELL-BEING

In the United Kingdom, the Office of National Statistics queries people on personal well-being, capturing the evaluative, emotional, and eudaimonic dimensions of subjective well-being (SWB) (121), by asking the questions shown below. Respondents provide answers on a 0–10 scale where 0 is "not at all" and 10 is "completely." These responses are aggregated to reflect well-being of the population surveys along the following three dimensions.

- Evaluative dimension:
    - Life satisfaction: Overall, how satisfied are you with your life nowadays?
    - Cantril ladder[1]: Please imagine a ladder with steps numbered from zero at the bottom to 10 at the top. The top of the ladder represents the best possible life for you and the bottom of the ladder represents the worst possible life for you. On which step of the ladder would you say you personally feel you stand at this time?
- Emotional dimension:
    - Happiness: Overall, how happy did you feel yesterday?
    - Anxiety: On a scale where 0 is "not at all anxious" and 10 is "completely anxious," overall, how anxious did you feel yesterday?
- Eudaimonic dimension:
    - Worthwhile: Overall, to what extent do you feel that the things you do in your life are worthwhile?

[1] Other surveys such as the Gallop worldwide happiness survey (287) include the above Cantril ladder of life question to assess the evaluative aspects of well-being.

### 3.2. Evaluating the Nexus Between Zero-Carbon Strategies and Health

Focusing on objective measures of health, Section 3.2 offers a synthesis of the mechanisms through which zero-carbon pathways impact human health outcomes. **Figure 6** provides a synthesis of these mechanisms.

**3.2.1. ZEC Strategy #1: Integrated spatial planning.** As noted in Section 3, integrated spatial planning is not just about population density; it includes thoughtful urban design leveraging all 5 Ds (density, diversity, neighborhood design, destination access (primarily to jobs), and distance to transit), which together are expected to result in reducing motorized travel demand, increase transit use (123, 124), and facilitate active mobility (walking and bicycling) (125). Evaluating the potential health benefits of integrated urban design must therefore be done carefully, addressing the confounding effects of population growth, the diversity of air pollution sources within cities in addition to vehicular emissions, including large point industrial sources that are patchy and vary across cities, and the self-selection of urban residents in central cities versus suburbs (126).

Focusing first solely on density, as expected, a large body of empirical studies yields mixed results in different geographies, due to the above confounding factors. For example, in India, population density is associated with greater air pollution due to the high concentration of people, industries, and vehicles, using biomass cooking fuels, coal and petrol fuels, respectively (7). On the other hand, efforts to shut down or relocate heavy industries outside of cities have also been shown to sharply reduce air pollution in cities, e.g., in Beijing during the 2008 Olympic Games (127, 128). Across cities in China, Chen et al. (129) reported reduced air pollution ($PM_{2.5}$ and $SO_2$) with increasing population density. In more developed nations, where industrial emissions are effectively controlled and household cooking fuels are cleaner, the impacts of fossil fuel–driven motorized vehicles may start to dominate. Carozzi & Roth (130) show increasing air pollution ($PM_{2.5}$) levels

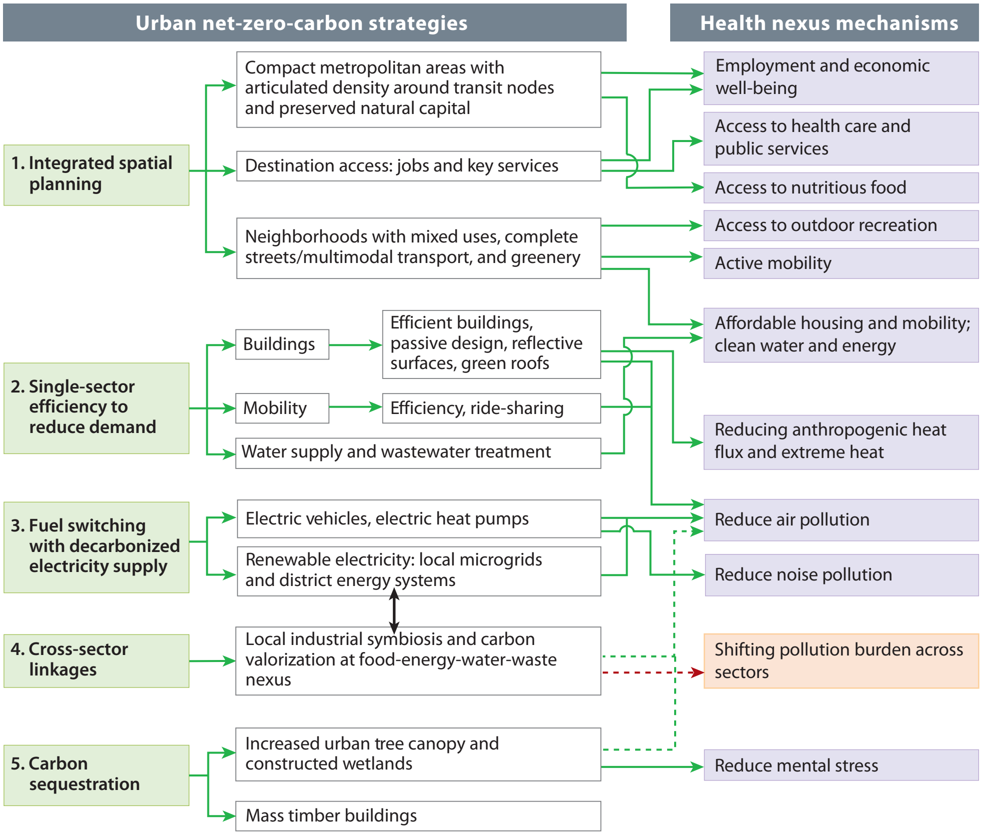


**Figure 6**

Schematic illustrating the nexus linkages between the broad decarbonization strategies and specific actions (*left two columns*), and potential health impacts (*right column*). Linkages to positive health impacts (*purple boxes*) are indicated via solid green lines; the green lines are dashed if the linkages are uncertain, while the dashed red lines show linkages to negative health impacts (*tan boxes*), i.e., health disbenefits. The black arrow indicates that carbon valorization at the food-energy-water-waste nexus can produce renewable natural gas that can be used in district energy systems.

with increasing city-level population density. Within cities, neighborhoods with greater proximity to roads (131) and industries (132) have been associated with greater air pollution exposures, as measured by mobile sensors, compared to other neighborhoods. The above articles focused on noncommunicable disease impacts. For the spread of pandemics, the consensus is that it is not population density per se but activity intensity (in schools and other enclosed spaces) which is a bigger contributor to disease spread within urban regions (133). Thus, the link between increasing population density and health benefits is mixed and situation-specific, requiring modeling alongside field measurements to unpack health impacts and risk exposures.

Overall, beyond population density, articulated density that enhances the 5 Ds has been found, through numerous careful studies that control for confounding factors (e.g., 82), to reduce motorized vehicle miles traveled per capita and increase transit and active mobility (134–136). These effects are summarized in the form of elasticity factors, derived from empirical studies in the United States (82) and increasingly in other nations [e.g., in China (137)], although country-specific elasticities are unavailable for most other nations (88). Elasticity factors have also been developed to model shifts toward transit and active mobility (138).

In the context of active mobility, public health studies find strong evidence that walking daily ~10,000 steps can help prevent cancer and cardiovascular disease incidence (139, 140). Pucher et al. (141) provide strong evidence of the health benefits of walkable and bikeable cities, reinforced in more recent studies comparing US neighborhoods with higher versus lower walk scores (140, 142). Given the above evidence base, integrated spatial planning that promotes transit and active mobility can be expected to contribute to public health as a public good available to all. However, pedestrians and cyclists can be at higher injury/mortality risk from accidents with larger vehicles, requiring care in design of multimodal streets (143) to maintain these health benefits. Lastly, because motorized mobility is dominated by fossil fuel vehicles, efforts to reduce motorized travel through urban planning are expected to reduce air pollution emissions, as evidenced in several studies showing the health benefits of various travel demand management policies in London, Delhi, etc. (144), as well as sharp reductions in air pollution seen with reduced travel during pandemics and recessions (145, 146). Additionally, there is significant evidence that urban greenery—a central part of integrated spatial planning—can improve health and well-being, discussed further under Strategy #5.

**3.2.2. ZEC Strategy #2: Single-sector efficiencies that reduce energy demand.** Conceptually, efficiency improvements in buildings and mobility sectors can improve health primarily via two key mechanisms—reducing fossil fuel–based air pollution and reducing associated anthropogenic heat fluxes that contribute to urban heat stress; the latter is discussed further in Section 4. To provide context, in 2018, mobility-related air pollution mortality in the United States was ~17,000 to 19,000 deaths per year (147), buildings electricity/power-plant attributable mortality was ~8,000–10,000 (148), and heat-related mortality was much lower, from 1,300 to 5,000 (61). Such quantitative estimates, incorporating heat risks, are not available for India or many other countries. We address efficiency interventions in mobility and building sectors here, describing their impact on air pollution and health. Impacts on extreme heat are discussed in Section 4 on resilience.

***3.2.2.1. Efficiency in the mobility sector.*** Fuel-efficient vehicles and vehicle fleets can reduce fossil fuel use and associated GHG emissions from the road transportation sector, but the effect on air pollutant emissions is confounded by the substantial role played by tailpipe pollution control. Indeed, a comprehensive study examining US transportation emissions from 2008 to 2017 (147), including analysis of counterfactuals, finds that GHG emissions from transportation actually increased slightly from 2008 to 2017, largely due to fleet shifts toward larger fuel-inefficient SUVs, while $PM_{2.5}$ emissions decreased by more than 50%, yielding substantial health benefits. The authors conclude that further reducing air pollution in metropolitan areas will require new forms of efficiency, achieved by either ride-sharing or shifts to EVs (described as the next strategy), in addition to reducing travel demand through spatial planning. A global study of transportation attributable mortality (149) found more-efficient diesel vehicles to be the largest contributors to mortality, followed by gasoline-driven vehicles in the passenger segments, indicating trade-offs between carbon and health. These studies highlight the complex interactions between vehicle/fleet fuel economy, fuel type, and pollution control technologies in achieving health benefits and underscore the need for air quality modeling with attention to local context. Examples include careful study of exposure to air pollution by individuals using different travel models [e.g., walking/bicycling in US cities (150) as well as auto rickshaws and transit in India (151)].

***3.2.2.2. Building efficiency.*** The air pollution–related health co-benefits of various building energy efficiency improvements (appliances, equipment, and building shell) are more straightforward, computed as avoided mortality from avoided gas use and/or avoided electricity generation at power plants. Examples show substantial reductions in premature mortality in the United States

(152) and disability-adjusted life-years (DALYs) in the United Kingdom (153). A review article (154) cautions, however, that tightening building envelopes for energy efficiency may increase indoor radon concentrations (without compensatory ventilation), creating substantial health disbenefits (155). Beyond reductions in air pollution, application of reflective surfaces increasing albedo in urban areas can mitigate heat stress (156), described further in the section on resilience (Section 4).

**3.2.3. ZEC Strategy #3: Fuel switching to electric heating and mobility with decarbonized electricity supply.** Similar to Strategy #2, there is a strong evidence base that adoption of electric heat pumps and EVs, which are more energy efficient than furnaces and combustion engines, respectively, can avoid fossil fuel use, which in turn is estimated to reduce air pollution–related mortality, e.g., by ∼14,000 avoided deaths annually in California in 2050 with full electrification of heating and mobility (157), and 40% reductions in annual premature deaths in a nationwide US study modeling rapid and aggressive energy sector decarbonization (158). Likewise, 25% US EV adoption, even with the added energy demand sourced from the present-day grid, is expected to annually avoid 535 deaths due to $PM_{2.5}$ reductions and lesser ozone formation (159). In China, a 27% electrification of private vehicles with an additional commercial fleet electrification by 2030 was estimated to result in ∼17,000 premature deaths avoided annually through local air quality improvements (160). These benefits are expected to increase with the fully zero-carbon electric grid, and similar trends are expected globally. EVs can also reduce noise pollution locally, a significant risk factor in urban areas (161). However, massive proliferation of lithium and other batteries and their recycling can create pollution at mine/recycling sites, shifting pollution burden to rural areas or other less developed countries (162); these potential transboundary burden shifts are less studied at present.

**3.2.4. ZEC Strategy #4: Cross-sector linkages.** Cross-sector linkages that contribute to decarbonization include urban-industrial symbiosis and carbon valorization at the FEWW nexus. Urban-industrial symbiosis, i.e., exchange of waste materials and low-grade heat between industries and between industries and residences through advanced district energy systems, is projected to result in ∼25,500 to ∼57,500 deaths avoided annually in China via avoided fossil fuel use and associated air pollution reduction (33). Similar scenario studies in India with power plant and industrial waste-heat reuse in district energy systems were estimated to avoid ∼130–36,000 mortalities annually (163). However, some of these projected health benefits will reduce when the grid decarbonizes, highlighting the importance of clarifying the reference/counterfactual cases. Substantial mitigation of air pollution and GHG emissions has been reported in a comprehensive study of eco-industrial parks in China (164). Carbon valorization at the FEWW nexus including food waste as well as crop waste for generating biomethane and biohydrogen (165, 166) is a key strategy for decarbonization, although pollution and other health disbenefits are yet unknown due to limited life cycle analysis.

**3.2.5. ZEC Strategy #5: Carbon sequestration.** Enhancing carbon uptake and stocks via maintaining and expanding urban tree canopy may yield health benefits, albeit context dependent (167, 168), and with the precise mechanisms, i.e., physical, mental, and social well-being, yet unknown (169, 170). Reduced stress is one key mechanism that most studies emphasize, which also contributes to SWB. In the context of mass timber buildings, substantial substitution of reinforced concrete buildings with wood can result in indirect benefits from reduced production of cement and steel, and associated air pollution emissions. Life cycle studies suggest mass timber buildings compared to steel buildings yield lower $PM_{2.5}$ emissions and eutrophication potential but greater smog potential (171), likely due to volatile organic compounds (VOCs) released from adhesives, suggesting uncertainty in net human health outcomes for mass timber building transitions. Improved designs such as dowel-laminated timber in place of glulam can mitigate VOC emissions.

Overall, the evidence base is very strong that well-designed ZEC strategies can indeed contribute to substantial health co-benefits; however, care must be taken to avoid burden shifting across risks (e.g., increasing accident risks to pedestrians) and to other sectors or locations (e.g., due to lithium mining for batteries or generation of toxic VOCs from glulam), where detailed life cycle assessments of new technologies will be important. To date, no study has quantified the health co-benefits/trade-offs of all five decarbonization strategies together, including complex nexus interactions detailed above. Such nexus modeling is a frontier research topic, critical to ensure health co-benefits of zero-carbon transitions.

## 3.3. Evaluating the Nexus Between Zero-Carbon Strategies and Well-Being

In addition to the health benefits from avoiding pollution-related disease burden described in Section 3.2, urban zero-carbon strategies can also enhance SWB. Most of this literature focuses on integrated spatial planning and urban greenery, and is briefly summarized below.

**3.3.1. ZEC Strategy #1: Integrated spatial planning.** Compact development through diversity of land uses has been found to improve accessibility of neighborhood and city services (public facilities, transportation, education, finance, health, etc.), which are positively associated with both evaluative and emotional SWB (172–177). Such development has also been linked to higher satisfaction with social relationships (178), which in turn is found to improve both evaluative SWB (179–182) and in some cases emotional SWB (176). However, the strength of these associations can vary by sociodemographics.

Design and diversity of land uses are also associated with increased walking- and biking-related physical activities, which have been linked to higher evaluative and emotional SWB, self-reported mental and physical health, including reductions in all-cause mortality, cardiovascular disease, type 2 diabetes, weight gain, and certain cancers (178, 183–185). Additionally, residential density and availability of destinations are associated with higher rates of using public transportation, which in combination with walking and biking have been associated with a lower risk of obesity and diabetes (142). In highly populated Asian cities, population density has been found to have an inverse U-shape association with walking for leisure (186). Additionally, scenario analyses of compact cities with higher land use diversity and density and lower distances to public transport have anticipated health gains for certain disease states including diabetes, cardiovascular disease, and respiratory disease and overall anticipated health gains of 420–826 DALYs per 100,000 population (134).

However, SWB disbenefits of density and diversity are also noted, including safety concerns (179, 187–189), congestion, overcrowding, and noise (174, 177, 187, 190, 191). Addressing these disbenefits can maximize the benefits of compact development, particularly in a future with EVs whose electric drives are inherently quiet.

**3.3.2. ZEC Strategy #1 and #5.** Another aspect of integrated spatial planning that also contributes to carbon sequestration is preserving natural capital in the form of green infrastructure. Satisfaction with and access to green infrastructure have been positively associated with both evaluative and emotional SWB (176, 192–194). Urban green areas have been found to directly and indirectly (via social interactions) mitigate stress (62). Green neighborhoods have been found to lower risks of poor mental health and cardiovascular disease, and are associated with higher levels of physical activity (195, 196). Urban agricultural gardens, a component of green infrastructure in urban areas, are also associated with higher emotional SWB (197, 198) and better health outcomes (for those who engage in urban agriculture), including better nutrition and healthier body mass indexes (199, 200). Although access to and quality of urban green infrastructure can have health and well-being benefits, research is needed to better understand the proportion of people engaged in household versus community gardening; Das & Ramaswami (201) find, in a study of 3 US cities, relatively small proportions of urban populations engaged in community gardening—which is more influenced by spatial planning and policy. However, this can vary widely, with some developing countries in Africa, Asia, and Central America indicating much larger urban population engagement in urban community agriculture (202). Thus, geographical and cultural contexts are critical in planning for and designing green infrastructure to maximize health and SWB benefits alongside zero-carbon goals.

## 4. CLIMATE RESILIENCE CO-BENEFITS OF URBAN ZERO-CARBON TRANSITIONS

### 4.1. Defining and Measuring Climate Resilience

Resilience has numerous definitions that have evolved over the past two decades (203–205; see also **Table 2** for a summary). Early definitions grounded in ecology and engineering focused on

**Table 2 Resilience definitions (adapted from References 204, 211, and 215)**

| Basic concept and focus | Definition | Example applications of infrastructure resilience focused on flooding risks, corresponding to different resilience definitions |
|---|---|---|
| Narrow resilience, initially drawn from ecology and engineered infrastructure resilience<br>Focus: return to a single stable equilibrium | Resilience as the ability to return to a stable equilibrium; focuses on recovery and constancy | Gray infrastructure engineering design for flood management focusing on fail-safe performance during disasters to enable return to prior conditions |
| Social resilience (also referred to as ecological resilience)<br>Focus: return to prior functionality, structure, and feedback by recognizing the importance of social systems for persistence and robustness | Capacity of a system (people + provisioning systems) to absorb disturbance and reorganize while undergoing changes to still retain essentially the same function, structure, identity, and feedback | Gray infrastructure for flood management that now includes people in early warning systems for evacuation planning along with gray infrastructure design |
| Social-ecological resilience, including engineered infrastructures<br>Focus: renewal of systems; enabling new trajectory and structures, through the capacities of social, ecological, and infrastructural systems, etc. | The capacity of social-ecological-infrastructural systems (SEIS) for adaptation, learning, and self-organization | Green-gray infrastructure for flood management that (in addition to the above) creates redundancy by incorporating nature-based solutions with conventional gray infrastructure for safe-to-fail stormwater networks |
| Community/urban resilience, applies social-ecological resilience ideas to cities or communities, encompassing social, infrastructural, and ecosystem capacities<br>Focus: community adaptation to climate risks | The capacities and capabilities of communities—in a system-of-systems fashion—to recover from disasters in an efficient amount of time and perform better in the future | Similar to the above, but applied to a community facing flooding risks, addressing its capacities and multisector interactions; capacities include social, economic, environmental, community capital, institutional, and infrastructural |
| Transformative resilience, applied to major infrastructure and food system transitions<br>Focus: looks to a new future through transformative technologies or policies rather than return to the past condition wherein human capabilities are enhanced overall through provisioning systems | The creation of fundamentally new SEIS systems to adapt to climate risks, with profound changes in social-ecological-infrastructure-technological systems that embrace the dynamic and rapidly changing risks | New futures can be enabled by transformative technology/infrastructure systems or major changes in urban land use (agriculture and forestry), all of which are part of zero-carbon transition pathways. New futures can also be driven by social priorities. |

returning to an original condition after exposure to a shock. However, because a return to unjust conditions may not be socially desirable, the terminology of building-back-better after disasters emerged, highlighting that shocks can also present opportunities to improve social, ecological and infrastructural functions (206). In the context of climate resilience, the shocks considered in this article include extreme heat, sea level rise, coastal flooding, and wildfire (see the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks).

A second strand of literature distinguishes between resilience as pathway versus resilience as outcome (203, 204). In the latter framing, infrastructure resilience is measured in terms of the time and spatial extent of infrastructure services recovery (e.g., power and mobility systems recovery after hurricanes) (207, 208). More recently, recognizing the interaction between engineered infrastructure and natural and social systems, the concept of social-ecological resilience, which emphasizes resilience as a feature of a system, has emerged. Under this conceptualization, resilience is measured by evaluating eco-infrastructure design using network simulation, focusing on three types of capacities: absorptive capacity, adaptive capacity, and restorative capacity (209, 210). Furthermore, typically network features for resilience, emerging from studies of mobility and power networks, include diversity, redundancy, and mitigating potential for cascading failures within both single-sector networks and across-sector networks.

A third strand of literature addresses community resilience, wherein the concept of social-ecological resilience is applied to address community-level response (rather than only engineered systems or ecosystem response) to climate change and disasters. Here, the emphasis includes organizational capacity for resilience, with concepts of social vulnerability and social learning incorporated into representations of resilience. In this framing, quantitative approaches to measure resilience (211) evaluate climate risk similar to health risk, described in Section 3.1. Here, climate risk is the multiplicative impact of the level of climate hazards (e.g., frequency and intensity of a storm event) multiplied by social vulnerability, which describes both physical exposure to storms or heat due to socioeconomic conditions as well as ability to cope with these impacts. Climate risk may be further modulated by dividing by an additional term that represents resilience capacity, i.e., capacities and capabilities of communities—in a system-of-systems fashion—to recover from disasters in an efficient amount of time and perform better in the future (211; see also 212). However, the metrics for resilience capacity vary widely and often include metrics such as for zero-carbon emissions which may not confer resilience benefits per se (213).

A fourth strand of literature distinguishes adaptive resilience from transformative resilience, wherein rather than return to a prior condition, transformative resilience describes the creation of fundamentally new systems to adapt to risks (214, 215). In this article, given that zero-carbon transitions involve new systemic changes, our focus is on transformative climate resilience offered by the zero-carbon transitions described in Section 2. We focus on the design implications of transforming physical provisioning systems, drawing on network simulations of mobility and energy systems, and landscape resilience for transboundary food, agricultural, and forestry systems (216, 217).

### 4.2. Evaluating the Nexus Between Zero-Carbon Strategies and Climate Resilience

We evaluate the evidence base through which zero-carbon pathways interact (negatively or positively) with resilience through transformation in urban form, new building technologies, power, and mobility networks. We also consider cross-sector interactions such as between trees, mobility, and power lines during hurricanes. **Figure 7** provides a synthesis summary of all these mechanisms.

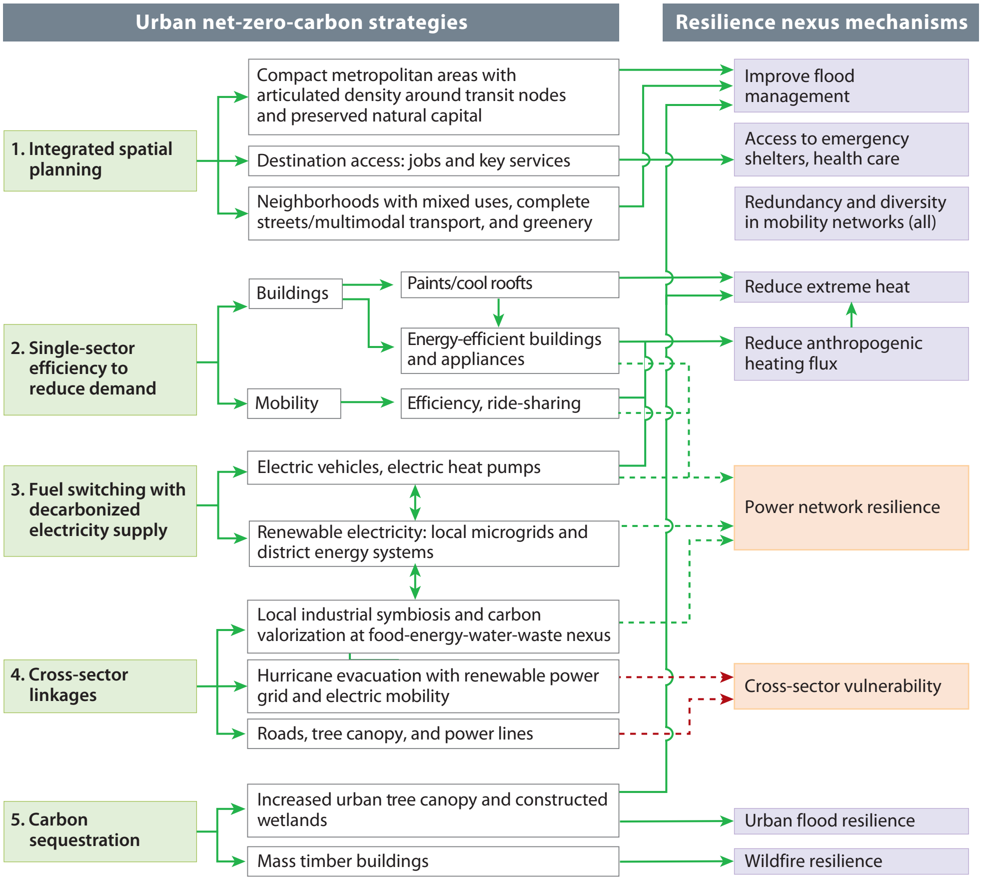


**Figure 7**

Schematic illustrating the nexus linkages between the broad decarbonization strategies, along with specific actions (*left two columns*), and potential resilience impacts (*right column*). Linkages to positive resilience impacts (*purple boxes*) are indicated via solid green lines; the green lines are dashed if linkages are uncertain, and the dashed red lines show linkages to negative impacts (*tan boxes*). For power network resilience, the tan box indicates that literature finds both positive and negative impacts on resilience representing uncertainty in directionality of impact.

### 4.2.1. ZEC Strategy #1: Integrated spatial planning.

Overall, there is broad consensus that a singular focus on resource efficiency through increased built area population density would be detrimental to climate resilience due to the loss of natural habitats, e.g., wetlands, lakes, and ponds (218–222). In contrast, a 5 D framework incorporating articulated density along with diversity of land uses, multimodal design, and intentional focus on preserving natural capital, particularly wetlands and lakes noted in the sponge city concept (223), can enhance climate resilience. However, there are very few models that have tested this hypothesis across diverse urban forms and climates with a range of climate hazards, as well as various mixes of green and gray infrastructures that will likely be important (89).

Overall, the main design guidelines are to balance urban densification with urban greenery and reforestation to address extreme heat and flooding, while also contributing to carbon sequestration for GHG mitigation. Furthermore, a well-designed compact city can be beneficial to community- and landscape-level resilience given reduced urban expansion in flood-prone areas (224) and agricultural lands (225), respectively. Finally, improved destination access to emergency shelters, health care, and evacuation routes—theoretically enabled by articulated density—is essential to reduce the secondary health effects of extreme events. Lim & Kain (226) highlight that the many 5 D features of compact cities are indeed consistent with resilience principles; however, practically implementing these in cities will require a combination of planning by design (long-term master planning), by code (design guides for blocks or neighborhoods), and by rules, e.g., prohibiting building in floodplains.

#### 4.2.2. ZEC Strategy #2: Single-sector efficiencies that reduce energy demand.

Energy-efficient vehicles and buildings can reduce fossil fuel use, which in turn reduces anthropogenic heat flux in the context of local heat stress. Reducing electricity demand, particularly peak demand during heat events, can also contribute to power grid resilience during extreme events, which we describe in the section on ZEC Strategy #3: electrification, below (see **Figure 7**).

Focusing on heat stress, early models recognized the importance of surface albedo (radiative heat transfer), evapotranspiration, and anthropogenic heat, although the last was assumed to be negligible, as is typical in less dense US cities (227). In contrast, a study of Tokyo in 1999 revealed the importance of anthropogenic heat flux in densely populated cities (228), reinforced in other Asian cities (229). Emerging models are recognizing that convective heat loss and urban canyon effects can be also substantial (230, 231). More recently, dynamic linkages with building energy system models show that increased air conditioning demand during heat waves can significantly increase anthropogenic heat flux, impacting local temperatures (232). Overall, increasingly fine-scale representations of building energy use, materials, and greenery, integrated with local microclimate models, nested within regional climate change models, are emerging to characterize urban heat.

However, to date, no studies have integrated all available heat mitigation strategies that have been reported individually in different cities, e.g., green and blue space (231), trees and paints (233), and district cooling systems (228) and EVs (234, 235) that reduce anthropogenic heat flux. This is a frontier area for urban microclimate modeling because many of these strategies can also reduce energy demand, benefiting decarbonization. However, there can be trade-offs. For example, conventional white paints and trees that reduce urban heat in summer can also increase energy demand in winter (236); widespread application of paints with broadband coolers can disrupt urban boundary layers, increasing air pollution (237); and selectively painting roofs upwind has potential to reduce urban heat downwind (156). Overall, the impact of vegetation in reducing urban heat, although variable within and across different cities, is reported to be on the order of 1 to 2°C in London (231) and in US cities including the impact of conventional white paints (233). The impact of reducing heat flux, likely small in less dense cities, can yield reductions of up to 1°C in dense Asian cities from shifts to district cooling in Japan (228) and vehicle electrification in Singapore (234, 235). However, the above levels of cooling may not be sufficient to address the extreme heat anticipated by 2100 (see the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks). Next-generation spectrally selective bidirectional metamaterials that can be deployed through low-cost paint to co-beneficially reduce energy use and generate as much as 6°C cooling in experimental studies are emerging (238). Passive building design utilizing these advanced materials combined with multiscale green infrastructure (street trees, large parks, water bodies, greenbelts) can potentially achieve both decarbonization and climate resilience to extreme heat, as well as extreme precipitation events, which is discussed further in the section on ZEC strategy #5.

**4.2.3. ZEC Strategy #3: Fuel switching to electric heating and mobility with decarbonized electricity supply.** ZEC Strategy #3 requires a decarbonized supply of energy, including provisioning of zero-carbon electricity and heat, as well as zeroing-out fossil fuel demand in heating and mobility by switching from fossil fuels to electricity-driven heat pumps in buildings and motors in electric vehicles. These supply side and demand side strategies are synergistic and are described in the following two sections.

***4.2.3.1. Zero-carbon electricity supply, local microgrids, and district energy systems.*** The electric power grid includes large-scale high-voltage transmission networks feeding into urban-scale distribution networks. The existing power system is highly vulnerable to disruption by climate events, with >90% of the disruptions over the past two decades attributed to extreme climate events (239). Hydropower and thermoelectric power generation requiring water for cooling are both particularly vulnerable to droughts (240). Transitions to a zero-carbon electric grid are expected to shift power generation to distributed and renewable energy resources, primarily solar and wind, supplemented with geothermal and bioenergy resources (30). Conceptually, the diversity of energy resources and their distributed nature can enhance network resilience (241) and also reduce future water vulnerability induced by large coal/thermoelectric and hydroelectric plants (240). However, researchers are also recognizing that reliably managing a very diverse zero-carbon energy portfolio with substantial intermittent generation from wind and solar, and increased demand from fuel switching to electric heating and mobility, can be challenging and exacerbated by climate events (242, 243). Furthermore, coupling a larger-scale zero-carbon generation-transmission system with fine-scale urban energy systems (zip code or neighborhood) with microgrids, rooftop solar, and district energy systems to quantify resilience benefits is very challenging and is a frontier topic of research (244). Without such nested models, assessing the resilience of the emerging multiscale zero-carbon energy system to multiple climate hazards is difficult. Key questions include the optimum mix of wind and solar versus renewable natural gas in terms of resilience of the larger grid, as well as of urban-scale distributed energy systems.

In general, the ability of urban areas to cost-effectively generate renewable energy locally through rooftop solar, solar energy–driven microgrids, and flex fuel–advanced district energy systems (245) that utilize multiple local resources (including industrial waste heat, urban tree waste, and renewable natural gas generated from municipal solid waste) is likely to contribute to the resilience of the overall energy system. Furthermore, a large body of literature indicates that these local microgrids and district energy systems can be islanded during climate extremes, offering community resilience (246, 247). Several papers have addressed the optimum siting of microgrids to serve critical facilities (hospitals and emergency shelters) as well as designing evacuation routes potentially using EVs during disasters (248, 249).

***4.2.3.2. Fuel switching to electrically driven heat pumps and electric mobility.*** There are mixed mechanisms by which EVs can impact resilience (positively or negatively). On the one hand, electric vehicle-to-grid integration can offer numerous resilience services to a future decarbonized power grid system by offering, for example, ancillary energy storage in batteries, energy storage during power outages, and peak shaving/valley filling by smart dynamic vehicle charging (219). However, there is debate among experts as to whether these benefits may be realized in practice (see 219) due to their dependence on emerging markets for resilience services as well as smart grid technologies, which are essential to minimize battery degradation (250). Furthermore, the interdependency of both energy and mobility systems can make both vulnerable to disruptions, with the potential to impair evacuations during hurricanes (251).

**4.2.4. ZEC Strategy #4: Cross-sector linkages.** Indeed, some cross-sector linkages can have negative impacts on power grid and community resilience. For example, trees impacted by high winds have potential to down power lines and disrupt mobility during hurricanes (252), which can be mitigated through tree trimming and other strategies (253). The interdependency of power and mobility systems can make both vulnerable during evacuations, as noted above (251). Moreover, power loss during hurricanes followed by heat waves can create compounded risks for affected populations (104). Other cross-sector linkages for decarbonization can enhance resilience. For example, urban-industrial symbiosis and carbon valorization at the FEWW nexus, such as leveraging local waste heat resources and organic waste to produce renewable natural gas for use in flex-fuel district energy systems, can enhance diversity of energy sources locally, contributing to energy system resilience during both extreme heat and extreme cold episodes. Valorization of biogenic carbon from food waste and wastewater can also generate biochar and nutrient-rich digestate that can contribute to decarbonization by reducing fertilizer application and enhancing carbon storage in soil, the latter of which can improve landscape resilience of farms (254), although there is much uncertainty about long-term carbon storage. Industrial symbiosis can also improve supply chain resilience by increasing redundancy and diversity (255), including for food systems (256).

**4.2.5. ZEC Strategy #5: Carbon sequestration.** Carbon sequestration by increasing urban tree canopy, wetlands, and mass timber buildings can offer multiple resilient co-benefits. As noted in the discussion on ZEC Strategy #2, increased tree canopy can mitigate heat stress and flooding from modest rainfall events (see, e.g., 257). Numerous studies show that estuarine wetlands can contribute substantially to coastal flood mitigation, with estimated savings of millions of dollars in damages (258, 259). The ability of urban constructed wetlands to mitigate peak storm flows has been demonstrated in numerous case studies designed for typical flooding events, e.g., 10-year flood return period, with Keeler et al. (89) noting substantial variability/uncertainties in measuring resilience benefits of urban nature-based solutions, particularly. Furthermore, coping with high-intensity, rare storms (e.g., with 500- or 5,000-year recurrence intervals) such as Hurricane Harvey will require substantial complementarity gray infrastructure in conjunction with nature-based solutions, e.g., sponge city designs, to minimize damages (260). Mass timber buildings, another strategy for carbon sequestration in urban areas, offer resilience to wildfires better than conventional wood-frame buildings (34, 261). Furthermore, carbon storage in the form of wood products, such as mass timber in urban construction, can enhance long-term storage in urban areas versus retaining wood in forests at risk. Sustainably harvesting timber products also can improve resilience of forests at risk from wildfires, as demonstrated in a recent case study of California, which in turn can reduce vulnerability of the power systems to wildfires (262). Multiscale and multisector models connecting building materials supply chains and power supply and wildfires are a new frontier in urban resilience modeling at the nexus with carbon sequestration.

Overall, the evidence base is mixed on the resilience co-benefits of urban zero-carbon pathways. Both positive and negative impacts on resilience are described in the literature and are difficult to quantify without the development of next-generation multiscale nested energy system models linked with multiple and multiscale climate risks. Such integrated modeling is known to be challenging. Furthermore, efforts to advance resilience to urban and coastal flooding through investments in gray infrastructure will increase demand for cement and concrete and may adversely impact pathways to zero-carbon cities. To date, there are few quantitative models that assess the material requirements of structural reinforcements needed to harden infrastructure to create resilient cities in the face of high winds and urban and coastal flooding. Such second-order interactions, presently unquantified, are also an important area of future research.

# 5. DESIGN FOR EQUITY

## 5.1. Defining and Measuring Social Inequality and Equity

Social inequality is different but related to social equity. In general, inequality describes empirical variation in the distribution of any urban systems attribute (e.g., income, access to infrastructure provisioning systems, and environmental hazard exposure). Efforts to measure inequality include population-wide measures of dispersion, such as relative standard deviation, Gini coefficient, as well as percentile ratios (P90/P10) and share ratios, comparing top and bottom percentages of the population. However, these do not inform social stratification effects explicitly.

Social equity, in contrast to population-level measures of inequality, addresses social stratification, including by class, caste, race, gender, disability status, and immigration status. Drawing on multiple literatures rooted in the Rawlsian theory of social justice (263–265), we define social equity as addressing fairness in the distribution of burdens and benefits across social groups, with the goal of reducing disparities for the most disadvantaged, across both determinants (e.g., income and infrastructure) and outcomes (e.g., health disparities) (10). In particular, Braveman (263) notes that fairness can be ambiguous and hence reducing inequalities (i.e., disparities) for the most disadvantaged must be stated explicitly. Distributional equity can be measured through population-stratified metrics such as disparity ratios across income or race (263). In urban areas, social stratification is often manifested spatially; thus analysis of inequality of various parameters (income, infrastructure access and use, pollution exposure, health outcomes) across neighborhoods by race and income can inform distributional equity (265).

The above definition of equity focuses on distributional outcomes. Increasingly, it is acknowledged that equity must include additional elements—procedural and recognitional (266). Procedural equity seeks to expand the participation of traditionally disadvantaged communities and social groups in decision-making processes that impact them, particularly those charting equitable futures. Recognitional equity recognizes systemic and historic contexts and constraints that have generated social disparities and shape pathways going forward—legal structures and cultural norms. Bozeman et al. (267) assert that addressing all three elements—distributive, procedural, and recognitional—is essential; leaving out any one will not result functionally in beneficial outcomes. Besides the three equity dimensions, reparational aspects (often used interchangeably with restorative equity) have also recently gained traction (268, 269).

In terms of social justice, varying definitions include Rawls's original conceptualization of justice and fairness, i.e., equal liberty principles, equal opportunity, and difference principles that allow differences in income associated with higher offices, as long as those positions are open to all (equal opportunity) and work to improve the least advantaged groups in society (270). More recently, justice is defined as efforts to remove barriers to achieve distributional equity (267). Therefore, in many ways, efforts that address all aspects of equity can often be considered synonymous with efforts to advance justice (10, 266).

## 5.2. Designing for Equitable Urban Zero-Carbon Transitions with Well-Being, Health, Equity, and Resilience Benefits

Distributive equity outcomes associated with the zero-carbon strategies cannot be assumed to occur naturally; instead, they will have to be designed explicitly to advance equity. We provide case examples that illustrate design for equity covering many of the zero-carbon strategies, using case examples from India and the United States.

**5.2.1. Equity case examples from India.** India is experiencing massive urbanization with >400 million more people expected to live in cities by 2050, as well as substantial inequality in infrastructure access both within and across cities (271). Therefore, developing inclusive infrastructure addressing both mobility as well as housing is a first step toward equity. Specific design strategies have emerged and shown success in case studies in India. These include land pooling and town planning schemes (32). In land pooling, rural farmers pool their land for infrastructure development in an organized manner. Rather than eminent domain, farmers retain their stake in the economic gains that accrue with urbanization; at the same time, urban development authorities ensure inclusive growth requirements, e.g., housing for economically weaker sections of society and land set aside for greenery, supporting long-term urban master planning as well as neighborhood-level equitable, mixed-income, and mixed-use housing (relevant to ZEC Strategy #1) with integration of nature-based solutions, important for resilience.

Well-designed urban planning schemes can also prevent slums formation. Concomitantly, slum rehabilitation efforts must ensure that slum dwellers are not displaced to job-inaccessible or disaster-prone neighborhoods. Case studies in Mumbai describe in situ slum rehabilitation wherein public, private, and community partnerships between local government, real-estate developers, and slum dwellers have resulted in multistory in situ slum rehabilitation. In this case, the developers bear the cost of constructing new high-rise buildings to government standards with water, electricity, and sanitation to rehabilitate slum dwellers, and in turn are allowed to develop on land previously occupied by their dense horizontally constructed informal settlements. The in situ rehabilitation also highlights procedural equity, with guidelines requiring engagement and approval of at least 70% of the slum dwellers (32, 272). With increases in heat stress expected in many cities in India, improved building designs can incorporate passive design principles to ensure that the multistory low-income housing can mitigate extreme heat stress (273).

In the context of equitable mobility transitions, most people in India (>80%) travel to work on foot, bicycles, two-wheelers, and buses; <20% use personal cars (8). Correspondingly, a case study of Delhi (8) attributed a preponderance of mobility-related air pollution (50–60%) and GHG emissions (35–60%) to the top 20% wealthiest households, who predominantly own cars (274). Nagpure et al. (8) found that prioritizing two-wheelers and bus transit electrification would substantially advance equity and decarbonization and air pollution mitigation (thereby benefiting health), compared to prioritizing charging infrastructure for the relatively smaller number of automobiles owned by the wealthiest households. To prevent environmental burden shifting, policies to collect and recycle batteries from battery-operated two-wheelers will be important to advance health systemically, alongside decarbonization and local $PM_{2.5}$ pollution mitigation. Similar to social inequality in mobility, lower-income areas in Delhi also have disproportionately lower tree canopy cover (275) as well as higher waste burning emissions (9), indicating additional sectors to prioritize at the intersection of health, equity, and zero-carbon goals.

### 5.2.2. Equity case examples from the United States.

The first step toward decarbonization—integrated spatial planning with articulated density—can advance social equity as demonstrated in an up-zoning policy recently adopted by the city of Minneapolis (276, 277), which enables a modest increase in density via single-family to multifamily duplex conversion—benefiting the 5 D approach, reducing motorized travel, and improving affordable housing, with equity and decarbonization benefits.

A second aspect relates to per capita floor area in residential buildings, which have been increasing worldwide (278), whereas there is substantial inequality with the highest income-quintiles having much larger floor areas. Our case study (37) found that multistory multifamily buildings had much smaller floor areas (1,786 $ft^2$ per multifamily housing unit compared to 2,177 $ft^2$ per single-family home in the illustrative city); the smaller homes benefit from reduced energy burden, particularly for lower-income households. Multifamily home construction is also conducive to mass timber adoption, creating a virtuous cycle that advances decarbonization and reduces energy burden, which is important for equity.

The third decarbonization strategy of single-sector efficiencies via adoption of green/passive new building standards, retrofitting older homes, and behavioral nudging via smart meters can reduce GHG emissions substantially (see **Figure 2*b***). A case study of Saint Paul, Minnesota (265), found a racial pattern after controlling for income, wherein neighborhoods with the highest nonwhite populations have higher energy use intensity reflecting less energy-efficient building stocks. The analysis enables spatial prioritization of neighborhoods for efficiency investments, unpacking income and racial inequality to advance equity. The study also highlighted that neighborhoods that are poor and have large nonwhite populations do not fully intersect with areas experiencing high energy burden nor those with high energy use intensity, emphasizing data-driven approaches to chart just energy transitions. The Biden administration in the US has also developed inequality metrics to prioritize energy efficiency investments in communities (279).

Addressing the fourth decarbonization strategy of vehicle electrification (280), a case study modeling air pollution benefits in New York City (105) demonstrated prioritizing future investments in zero-carbon mobility systems considering existing inequalities in access to low-cost transportation services as well as exposure to air pollution. Another study explored equity in access to charging infrastructure.

Similarly, inequality data can inform equity in deploying the fifth strategy—carbon sequestration by trees, wherein high levels of racial and income inequality have been observed in tree canopy coverage in US cities (281). However, tree-planting campaigns have not been effective in many low-income neighborhoods, wherein Riedman et al. (282) conducted field interviews to unpack underlying constraints and competing priorities, reflecting the application of recognition equity. Procedural equity is also critical to ensure urban residents participate and are engaged in the design of both tree maintenance and tree-planting programs (283). Overall, these examples demonstrate the importance of combining analysis of inequality data (distributional equity) in conjunction with recognition and procedural equity for sociospatial prioritization of zero-carbon strategies in cities.

No case study to date has addressed sociospatial design for equity considering all the zero-carbon strategies, together, considering the transboundary impacts as well on inequality due to jobs gained/lost as new technologies are deployed. Furthermore, there are no models available that address equity in health and climate resilience co-benefits of the five decarbonization strategies, addressing multiple climate hazards. This is particularly important because more than 60% of cities are expected to experience more than one climate hazard (see the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks).

## 6. SYNTHESIS AND DIRECTIONS FOR FUTURE RESEARCH

A focus on seven key provisioning systems enables urban areas to chart pathways to a zero-carbon future through a sequence of five zero-carbon (ZEC) strategies, and also evaluate their nexus linkages with WHER outcomes.

The literature indicates strong evidence that net-zero-carbon strategies can also yield net health and well-being co-benefits, with care taken to ensure health risks are not shifted to different sectors, locales, or risk factors. Local context and modeling are important in identifying which ZEC pathways yield the maximum co-benefits. There are currently no studies addressing the multiple environmental and infrastructural risk factors prevalent in cities, as well as potential compounded effects expected from all the zero-carbon pathways. Such integrated spatial models are urgently needed to quantify the nexus between decarbonization, health, and well-being.

In the context of resilience, the evidence is less clear that the sequence of five zero-carbon pathways will inherently align beneficially with climate resilience. The lack of strong evidence is due to a lack of multiple climate risk data across the more than 1,000 larger cities (with population >500,000) that exist in the world today (48)—indeed multirisk data covering all 5 main environmental risks (extreme heat/cold, hurricanes, wildfires, precipitation/drought, air pollution) are only available for a few risk factors and for the top 20 cities (see the sidebar titled Global Impact of Infrastructure and Food Provisioning Systems on Greenhouse Gas Emissions, Social Inequality, Health, and Climate Risks). Interactions among risk factors are not well studied, and there have been no comprehensive models that connect decarbonization strategies with resilience outcomes. Even in the most mature case of modeling of heat stress, different mechanisms to mitigate heat stress have not been investigated together in one city much less global cities.

In the context of equity, social equity will not be enabled automatically in zero-carbon transitions and will require intentional efforts to integrate distributional, procedural, and recognitional dimensions. Achieving equity while decarbonizing and achieving health and resilience co-benefits requires intentional design in the deployment of new technologies, spatial arrangement of infrastructure, spatial prioritization of interventions, and design of policies and procedures.

## SUMMARY POINTS

1. A transboundary urban metabolism framework, rooted in seven key infrastructure and food provisioning systems subject to multiple risk factors, connects urban decarbonization strategies with well-being, health, equity and resilience (WHER) outcomes.
2. The evidence base for co-beneficial decarbonization is strong for health, limited for well-being, and uncertain for resilience. Intentional design is needed to advance equity, including distributional, procedural, and recognitional aspects.
3. The evidence base, key knowledge gaps, and broad parameters of a new urban nexus science are delineated in this paper so as to enable zero-carbon urban transition with WHER co-benefits.

## FUTURE ISSUES

1. A new nexus science is needed for advancing decarbonization with well-being, health, equity, and resilience (WHER) co-benefits.
2. Fine-scale data for cities encompassing all sectors, scales, and risks including multiple infrastructure, pollution and climate risk factors, their integration, and their combined effects (interactions) will be imperative to advance the nexus science.
3. Next-generation nexus models must be developed that systematically inform policies and spatial design of zero-carbon pathways across multiple provisioning systems, making visible the potential trade-offs and co-benefits among zero-carbon and WHER outcomes.
4. New modalities for co-production are needed that enable scientists, policymakers, and practitioners to collaborate, integrating distributional, procedural, and recognition dimensions of equity to evaluate/choose alternative pathways/policy designs for decarbonizing with health, well-being, equity, and resilience.

## DISCLOSURE STATEMENT

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## LITERATURE CITED

1. The World Bank. 2022. Urban development. *The World Bank*. **https://www.worldbank.org/en/topic/urbandevelopment**
2. UNDESA (U.N. Dep. Econ. Soc. Aff.). 2018. 68% of the world population projected to live in urban areas by 2050, says UN. *United Nations News*, May 16. **https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html**
3. Ramaswami A. 2020. Unpacking the urban infrastructure nexus with environment, health, livability, well-being, and equity. *One Earth* 2(2):120–24
4. U.N. Environ. Progr. 2017. Cities. *UN Environment Programme*. **https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities**
5. Glaeser E. 2012. *Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier, and Happier*. London: Penguin
6. UNDESA (U.N. Dep. Econ. Soc. Aff.). 2020. *World Social Report 2020: Inequality in a rapidly changing world*. Rep., UNESDA, New York
7. Pant P, Lal RM, Guttikunda SK, Russell AG, Nagpure AS, et al. 2019. Monitoring particulate matter in India: recent trends and future outlook. *Air Qual. Atmos. Health* 12(1):45–58
8. Nagpure AS, Tong K, Ramaswami A. 2022. Socially-differentiated urban metabolism methodology informs equity in coupled carbon-air pollution mitigation strategies: insights from three Indian cities. *Environ. Res. Lett.* 17(9):094025
9. Nagpure AS, Ramaswami A, Russell A. 2015. Characterizing the spatial and temporal patterns of open burning of municipal solid waste (MSW) in Indian cities. *Environ. Sci. Technol.* 49(21):12904–12
10. Clark LP, Tabory S, Tong K, Servadio JL, Kappler K, et al. 2022. A data framework for assessing social inequality and equity in multi-sector social, ecological, infrastructural urban systems: focus on fine-spatial scales. *J. Ind. Ecol.* 26(1):145–63
11. Va. Commonw. Univ. Cent. Soc. Health. 2016. Mapping life expectancy. *Virginia Commonwealth University*. **https://societyhealth.vcu.edu/work/the-projects/mapping-life-expectancy.html**
12. Seto KC, Dhakal S, Bigio A, Blanco H, Delgado GC, et al. 2014. Human settlements, infrastructure and spatial planning. In *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. O Edenhofer, R Pichs-Madruga, Y Sokona, E Farahani, S Kadner, et al., pp. 923–1000. Cambridge, UK: Cambridge Univ. Press
13. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, et al., eds. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press. 1132 pp.
14. Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, et al. 2009. Greenhouse gas emissions from global cities. *Environ. Sci. Technol.* 43(19):7297–302
15. Ramaswami A, Hillman T, Janson B, Reiner M, Thomas G. 2008. A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories. *Environ. Sci. Technol.* 42(17):6455–61
16. Ramaswami A, Tong K, Canadell JG, Jackson RB, Stokes E, et al. 2021. Carbon analytics for net-zero emissions sustainable cities. *Nat. Sustain.* 4(6):460–63

17. Chavez A, Ramaswami A. 2013. Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: mathematical relationships and policy relevance. *Energy Policy* 54:376–84
18. ICLEI–Local Gov. Sustain. USA. 2019. *U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions*. Rep., ICLEI–Local Gov. Sustain. USA, Denver
19. Fong WK, Sotos M, Doust M, Schultz S, Marquez A, et al. 2014. *Global Protocol for Community-Scale Greenhouse Gas Emission Inventories*. Rep., World Resour. Inst., Washington, DC/C40 Cities Clim. Leadersh. Group, London/ICLEI–Local Gov. Sustain., Bonn, Ger.
20. Ramaswami A, Russell AG, Culligan PJ, Sharma KR, Kumar E. 2016. Meta-principles for developing smart, sustainable, and healthy cities. *Science* 352(6288):940–43
21. C40 (C40 Cities Clim. Leadersh. Group), Arup. 2014. *Working together: global aggregation of city climate commitments.* **https://www.arup.com/perspectives/publications/research/section/working-together-global-aggregation-of-city-climate-commitments**
22. U.N. Clim. Change Conv. 2022. Race to Zero campaign. *United Nations Climate Change Convention*. **https://racetozero.unfccc.int/system/race-to-zero/**
23. Seto KC, Churkina G, Hsu A, Keller M, Newman PW, et al. 2021. From low- to net-zero carbon cities: the next global agenda. *Annu. Rev. Environ. Resour.* 46:377–415
24. Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, et al. 2018. Net-zero emissions energy systems. *Science* 360(6396):eaas9793
25. Azevedo I, Bataille C, Bistline J, Clarke L, Davis S. 2021. Net-zero emissions energy systems: what we know and do not know. *Energy Clim. Change* 2:100049
26. Shukla P, Dhar S, Pathak M, Mahadevia D, Garg A. 2015. *Pathways to deep decarbonization in India*. Paris: SDSN, IDDRI. **https://ddpinitiative.org/wp-content/pdf/DDPP_IND.pdf**
27. Teng F, Gu A, Yang X, Wang X, Liu Q, et al. 2015. *Pathways to deep decarbonization in China*. Paris: SDSN, IDDRI. **https://ddpinitiative.org/wp-content/pdf/DDPP_CHN.pdf**
28. Altieri K, Trollip H, Caetano T, Hughes A, Merven B, Winkler H. 2015. *Pathways to deep decarbonization in South Africa*. Paris: SDSN, IDDRI. **https://ddpinitiative.org/wp-content/pdf/DDPP_ZAF.pdf**
29. Larson E, Greig C, Jenkins J, Mayfield E, Pascale A, et al. 2021. *Net-zero America: potential pathways, infrastructure, and impacts.* Rep., Princeton Univ., Princeton, NJ
30. Jenkins JD, Mayfield EN, Larson ED, Pacala SW, Greig C. 2021. Mission net-zero America: the nation-building path to a prosperous, net-zero emissions economy. *Joule* 5(11):2755–61
31. Hsu D, Andrews CJ, Han AT, Loh CG, Osland AC, Zegras CP. 2022. Planning the built environment and land use towards deep decarbonization of the United States. *J. Plan. Lit.* 38(3):426–41. **https://doi.org/10.1177/08854122221097977**
32. Swilling M, Hajer M, Baynes T, Bergesen J, Labbé F, et al. 2018. *The weight of cities: resource requirements of future urbanization. Summary for policy makers*, Rep., Int. Resour. Panel, UNEP, Nairobi, Kenya
33. Ramaswami A, Tong K, Fang A, Lal RM, Nagpure AS, et al. 2017. Urban cross-sector actions for carbon mitigation with local health co-benefits in China. *Nat. Clim. Change* 7(10):736–42
34. Churkina G, Organschi A, Reyer CPO, Ruff A, Vinke K, et al. 2020. Buildings as a global carbon sink. *Nat. Sustain.* 3(4):269–76
35. Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, et al. 2021. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nat. Commun.* 12(1):5097
36. Teo HC, Zeng Y, Sarira TV, Fung TK, Zheng Q, et al. 2021. Global urban reforestation can be an important natural climate solution. *Environ. Res. Lett.* 16(3):034059
37. Ramaswami A. 2021. Multi-sector modeling for net-zero carbon and equitable cities: Implementation in Twin Cities, USA. *AGU Fall Meet. Abstr.* 2021:GC11B-03
38. City of New York. 2019. *One New York: The Plan for a Strong and Just City*. **https://www.nyc.gov/html/onenyc/downloads/pdf/publications/OneNYC.pdf**
39. American Heart Association. 2020. *American Heart Association's strategic policy agenda 2020–2022*. Rep., Am. Heart Assoc., Advocacy Dep., Washington, DC. **https://www.heart.org/-/media/Files/About-Us/Policy-Research/Policy-Reports/Strategic-Policy-Agenda2-pager–2020.pdf**

40. Herrmann A, Lenzer B, Müller BS, Danquah I, Nadeau KC, et al. 2022. Integrating planetary health into clinical guidelines to sustainably transform health care. *Lancet Planet. Health* 6(3):e184–85
41. O'Neill DW, Fanning AL, Lamb WF, Steinberger JK. 2018. A good life for all within planetary boundaries. *Nat. Sustain.* 1(2):88–95
42. Chester MV. 2019. Sustainability and infrastructure challenges. *Nat. Sustain.* 2(4):265–66
43. Rao ND, Min J. 2018. Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.* 138(1):225–44
44. Ramaswami A. 2020. Unpacking the urban infrastructure nexus with environment, health, livability, well-being, and equity. *One Earth* 2(2):120–24
45. Oswald Y, Owen A, Steinberger JK. 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nat. Energy* 5(3):231–39
46. UNEP (U.N. Environ. Progr.). 2019. First ever Cities Summit calls for integrated approach to urban infrastructure. *United Nations Environment Programme*, March 27. **https://www.unep.org/news-and-stories/story/first-ever-cities-summit-calls-integrated-approach-urban-infrastructure**
47. Ramaswami A, Weible C, Main D, Heikkila T, Siddiki S, et al. 2012. A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems: an integrative curriculum across seven major disciplines. *J. Ind. Ecol.* 16(6):801–13
48. UNDESA (U.N. Dep. Econ. Soc. Aff., Popul. Div.). 2018. *The World's Cities in 2018: data booklet*. Rep., U.N., New York. **https://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2018_data_booklet.pdf**
49. Nagpure AS, Reiner M, Ramaswami A. 2018. Resource requirements of inclusive urban development in India: insights from ten cities. *Environ. Res. Lett.* 13(2):025010
50. Mitchell BC, Chakraborty J, Basu P. 2021. Social inequities in urban heat and greenspace: analyzing climate justice in Delhi, India. *Int. J. Environ. Res. Public Health* 18(9):4800
51. Boyer D, Sarkar J, Ramaswami A. 2019. Diets, food miles, and environmental sustainability of urban food systems: analysis of nine Indian cities. *Earth's Future* 7(8):911–22
52. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, et al., eds. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge Univ. Press
53. UNSD (U.N. Stat. Div.). 2022. *Sustainable Development Goals. Goal 11: Make cities inclusive, safe, resilient and sustainable*. United Nations, New York. **https://www.un.org/sustainabledevelopment/cities/**
54. UN-HABITAT (U.N. Hum. Settl. Progr.). 2010. *State of the World's Cities 2010/2011—cities for all: bridging the urban divide*. Rep., UN-HABITAT, Nairobi
55. Capone D, Cumming O, Nichols D, Brown J. 2020. Water and sanitation in urban America, 2017–2019. *Am. J. Public Health* 110(10):1567–72
56. Ramaswami A, Russell AG, Culligan PJ, Sharma KR, Kumar E. 2016. Meta-principles for developing smart, sustainable, and healthy cities. *Science* 352(6288):940–43
57. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, et al. 2018. The *Lancet* Commission on pollution and health. *Lancet North Am. Ed.* 391(10119):462–512
58. Dye C. 2008. Health and urban living. *Science* 319(5864):766–69
59. Ritchie H, Rosado P, Roser M. 2019. Natural disasters. *OurWorldInData.org*. **https://ourworldindata.org/natural-disasters**
60. WHO (World Health Organ.). 2011. *Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe*. Bonn, Ger.: WHO
61. Weinberger KR, Harris D, Spangler KR, Zanobetti A, Wellenius GA. 2020. Estimating the number of excess deaths attributable to heat in 297 United States counties. *Environ. Epidemiol.* 4(3):e096
62. Fan Y, Das KV, Chen Q. 2011. Neighborhood green, social support, physical activity, and stress: assessing the cumulative impact. *Health Place* 17(6):1202–11
63. Tuholske C, Caylor K, Funk C, Verdin A, Sweeney S, et al. 2021. Global urban population exposure to extreme heat. *PNAS* 118(41):e2024792118
64. Varquez ACG, Kanda M. 2018. Global urban climatology: a meta-analysis of air temperature trends (1960–2009). *npj Clim. Atmos Sci.* 1:32

65. Vargas Zeppetello LR, Raftery AE, Battisti DS. 2022. Probabilistic projections of increased heat stress driven by climate change. *Commun. Earth Environ.* 3(1):183
66. Cao W, Zhou Y, Güneralp B, Li X, Zhao K, Zhang H. 2022. Increasing global urban exposure to flooding: an analysis of long-term annual dynamics. *Sci. Total Environ.* 817:153012
67. Smith AB, Katz RW. 2013. US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Nat. Hazards* 67(2):387–410
68. Studholme J, Fedorov AV, Gulev SK, Emanuel K, Hodges K. 2022. Poleward expansion of tropical cyclone latitudes in warming climates. *Nat. Geosci.* 15(1):14–28
69. Radeloff VC, Helmers DP, Kramer HA, Mockrin MH, Alexandre PM, et al. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. *PNAS* 115(13):3314–19
70. Wiedmann T, Chen G, Owen A, Lenzen M, Doust M, et al. 2021. Three-scope carbon emission inventories of global cities. *J. Ind. Ecol.* 25(3):735–50
71. Tong K, Fang A, Boyer D, Hu Y, Cui S, et al. 2016. Greenhouse gas emissions from key infrastructure sectors in larger and smaller Chinese cities: method development and benchmarking. *Carbon Manag.* 7(1–2):27–39
72. Lin J, Hu Y, Cui S, Kang J, Ramaswami A. 2015. Tracking urban carbon footprints from production and consumption perspectives. *Environ. Res. Lett.* 10(5):054001
73. Milnar M, Ramaswami A. 2021. Database update: impact of urban expansion and in situ greenery on community-wide carbon emissions: method development and insights from 11 US cities. *Environ. Sci. Technol.* 55(8):5597–600
74. Markolf SA, Matthews HS, Azevedo IL, Hendrickson C. 2017. An integrated approach for estimating greenhouse gas emissions from 100 U.S. metropolitan areas. *Environ. Res. Lett.* 12(2):024003
75. Markolf SA, Matthews HS, Azevedo IML, Hendrickson C. 2018. The implications of scope and boundary choice on the establishment and success of metropolitan greenhouse gas reduction targets in the United States. *Environ. Res. Lett.* 13(12):124015
76. Creutzig F, Niamir L, Bai X, Callaghan M, Cullen J, et al. 2022. Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat. Clim. Change* 12(1):36–46
77. Argonne Natl. Lab. 2021. *GREET: the greenhouse gases, regulated emissions, and energy use in technologies model*. Factsheet, Argonne Natl. Lab., Lemont, IL. **https://www.anl.gov/sites/www/files/2020-10/GREET_Impact_Sheet.pdf**
78. Cropp J, Lee A, Castor S. 2014. Evaluating results for LEED buildings in an energy efficiency program. In *Proceedings of the 2014 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA*, pp. 3-63–74. **https://www.aceee.org/files/proceedings/2014/data/papers/3-368.pdf**
79. Azevedo I, Davidson MR, Jenkins JD, Karplus VJ, Victor DG. 2020. The paths to net zero: how technology can save the planet. *Foreign Aff.* 99(3):18–27
80. Lu L, Guest JS, Peters CA, Zhu X, Rau GH, Ren ZJ. 2018. Wastewater treatment for carbon capture and utilization. *Nat. Sustain.* 1(12):750–58
81. Nowak DJ, Greenfield EJ, Hoehn RE, Lapoint E. 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* 178:229–36
82. Ewing R, Cervero R. 2010. Travel and the built environment. *J. Am. Plan. Assoc.* 76(3):265–94
83. Ramaswami A, Tabory S, McFarlane AA, Pelton RE. 2018. *Sustainable urban infrastructure transitions in the ASEAN region: a resource perspective.* U.N. Environ. Progr. Int. Resour. Panel, DTI/2184/PA UNEP 190. **https://wedocs.unep.org/handle/20.500.11822/31582**
84. ESMAP (Energy Sector Manag. Assis. Progr.). 2014. *Planning energy efficient and livable cities*. Mayoral Guidance Note 6, ESMAP, World Bank, Washington, DC
85. Global Platform for Sustainable Cities. 2020. *A Review of Integrated Urban Planning Tools for Greenhouse Gas Mitigation.* Washington, DC: World Bank. **https://doi.org/doi:10.1596/33784**
86. Fagnant DJ, Kockelman KM. 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transp. Res. C.* 40:1–13
87. Chertow MR. 2000. Industrial symbiosis: literature and taxonomy. *Annu. Rev. Energy Environ.* 25:313–37
88. Hepburn C, Adlen E, Beddington J, Carter EA, Fuss S, et al. 2019. The technological and economic prospects for $CO_2$ utilization and removal. *Nature* 575(7781):87–97

89. Keeler BL, Hamel P, McPhearson T, Hamann MH, Donahue ML, et al. 2019. Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustain.* 2(1):29–38
90. Smith IA, Dearborn VK, Hutyra LR. 2019. Live fast, die young: accelerated growth, mortality, and turnover in street trees. *PLOS ONE* 14(5):e0215846
91. World Health Organ. Reg. Off. East. Mediterr. 1995. *Constitution of the World Health Organization.* **https://apps.who.int/iris/handle/10665/121457**
92. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet North Am. Ed.* 380(9859):2224–60
93. IHME (Inst. Health Metr. Eval.). 2022. Global burden of disease (GBD). *Institute for Health Metrics and Evaluation.* **https://www.healthdata.org/research-analysis/gbd**
94. Ramaswami A, Nagpure A. 2023. The urban burden of disease pre-COVID: unpacking infrastructure, food supply and environmental risk factors across cities in India. *Nat. Sustain.* 136:104265
95. CDC-PLACES. 2022. PLACES: Local Data for Better Health. *Centers for Disease Control and Prevention.* **https://www.cdc.gov/places/index.html**
96. Tessum CW, Apte JS, Goodkind AL, Muller NZ, Mullins KA, et al. 2019. Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure. *PNAS* 116(13):6001–6
97. Wilkinson R, Marmot M, WHO (World Health Organ.). 2003. *Social Determinants of Health—The Solid Facts*. Copenhagen: WHO. 2nd ed.
98. Ostro B. 2004. *Outdoor Air Pollution: Assessing the Environmental Burden of Disease at National and Local Levels*. Geneva: World Health Organ.
99. IHME (Inst. Health Metr. Eval.). 2019. Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2019 (GBD 2019) results. Seattle, United States. *Institute for Health Metrics and Evaluation*. **https://vizhub.healthdata.org/gbd-compare/**
100. UNDRR (U.N. Off. Disaster Risk Reduct.). 2021. Disaster losses & statistics. *United Nations Office for Disaster Risk Reduction*. **https://www.preventionweb.net/understanding-disaster-risk/disaster-losses-and-statistics**
101. Vos T, Lim SS, Abbafati C, Abbas KM, Abbasi M, et al. 2020. Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet North Am. Ed.* 396(10258):1204–22
102. Gidlöf-Gunnarsson A, Öhrström E. 2007. Noise and well-being in urban residential environments: the potential role of perceived availability to nearby green areas. *Landsc. Urban Plan.* 83(2–3):115–26
103. Halperin D. 2014. Environmental noise and sleep disturbances: A threat to health? *Sleep Sci*. 7(4):209–12
104. Feng K, Ouyang M, Lin N. 2022. Tropical cyclone-blackout-heatwave compound hazard resilience in a changing climate. *Nat. Commun.* 13:4421
105. Shukla K, Seppanen C, Naess B, Chang C, Cooley D, et al. 2022. ZIP code-level estimation of air quality and health risk due to particulate matter pollution in New York City. *Environ. Sci. Technol.* 56(11):7119–30
106. Liu J, Clark LP, Bechle MJ, Hajat A, Kim S-Y, et al. 2021. Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environ. Health Perspect.* 129(12):127005
107. Feng C, Jiao J. 2021. Predicting and mapping neighborhood-scale health outcomes: a machine learning approach. *Comput. Environ. Urban Syst.* 85:101562
108. Southerland VA, Brauer M, Mohegh A, Hammer MS, van Donkelaar A, et al. 2022. Global urban temporal trends in fine particulate matter ($PM_{2.5}$) and attributable health burdens: estimates from global datasets. *Lancet Planet. Health* 6(2):e139–46
109. CDC (Cent. Disease Control Prev.). 2022. *Adult physical inactivity prevalence maps by race/ethnicity*. CDC, Atlanta. **https://www.cdc.gov/physicalactivity/data/inactivity-prevalence-maps/index.html**
110. Lee SH, Moore L, Park S, Harris D, Blanck H. 2022. Adults meeting fruit and vegetable intake recommendations—United States, 2019. *MMWR Wkly.* 71(1):1–9
111. Shiels MS, Haque AT, Berrington de González A, Freedman ND. 2022. Leading causes of death in the US during the COVID-19 pandemic, March 2020 to October 2021. *JAMA Intern. Med.* 182(8):883–86
112. RGI (Regist. Gen. Census Comm. India). 2022. *Report on Medical Certification of Cause of Death*. Rep., Off. Regist. Gen., India. Gov. India, Minist. Home Aff., Vital Stat. Div., R.K. Puram,

New Delhi. **https://censusindia.gov.in/nada/index.php/catalog/42681/download/46350/Annual_Report_on_MCCD_2020.pdf**

113. Aleta A, Martín-Corral D, Bakker MA, Pastore y Piontti A, Ajelli M, et al. 2022. Quantifying the importance and location of SARS-CoV-2 transmission events in large metropolitan areas. *PNAS* 119(26):e2112182119
114. Chang S, Pierson E, Koh PW, Gerardin J, Redbird B, et al. 2021. Mobility network models of COVID-19 explain inequities and inform reopening. *Nature* 589(7840):82–87
115. Zhang X, Sun Z, Ashcroft T, Dozier M, Ostrishko K, et al. 2022. Compact cities and the Covid-19 pandemic: systematic review of the associations between transmission of Covid-19 or other respiratory viruses and population density or other features of neighbourhood design. *Health Place* 76:102827
116. Pandey B, Gu J, Ramaswami A. 2022. Characterizing COVID-19 waves in urban and rural districts of India. *npj Urban Sustain*. 2(1):26
117. Bertozzi AL, Franco E, Mohler G, Short MB, Sledge D. 2020. The challenges of modeling and forecasting the spread of COVID-19. *PNAS* 117(29):16732–38
118. Durand M. 2015. The OECD better life initiative: *How's Life?* and the measurement of well-being. *Rev. Income Wealth* 61(1):4–17
119. Helliwell JF, Barrington-Leigh CP. 2010. Measuring and understanding subjective well-being. *Can. J. Econ.* 43(3):729–53
120. Kahneman D, Deaton A. 2010. High income improves evaluation of life but not emotional well-being. *PNAS* 107(38):16489–93
121. ONS (Off. Natl. Stat.). 2018. Personal well-being user guidance. *Office for National Statistics*. **https://www.ons.gov.uk/peoplepopulationandcommunity/wellbeing/methodologies/personalwellbeingsurveyuserguide**
122. Helliwell JF, Layard R, Sachs JD, De Neve JE, Aknin LB, Wang S. 2022. *World Happiness Report 2022*. Rep., Sustain. Dev. Solut. Netw., New York
123. Cervero R, Kockelman K. 1997. Travel demand and the 3Ds: density, diversity, and design. *Transp. Res. D.* 2(3):199–219
124. Rodier C. 2009. Review of international modeling literature: Transit, land use, and auto pricing strategies to reduce vehicle miles traveled and greenhouse gas emissions. *Transp. Res. Rec.* 2132(1):1–12
125. Nieuwenhuijsen MJ. 2020. Urban and transport planning pathways to carbon neutral, liveable and healthy cities; a review of the current evidence. *Environ. Int.* 140:105661
126. National Research Council. 2009. *Driving and the built environment: the effects of compact development on motorized travel, energy use, and* $CO_2$ *emissions.* Spec. Rep. 298. Washington, DC: The Natl. Acad. Press. **https://doi.org/10.17226/12747**
127. Rich DQ, Kipen HM, Huang W, Wang G, Wang Y, et al. 2012. Association between changes in air pollution levels during the Beijing Olympics and biomarkers of inflammation and thrombosis in healthy young adults. *JAMA* 307(19):2068–78
128. Wang M, Zhu T, Zheng J, Zhang RY, Zhang SQ, et al. 2009. Use of a mobile laboratory to evaluate changes in on-road air pollutants during the Beijing 2008 Summer Olympics. *Atmos. Chem. Phys.* 9(21):8247–63
129. Chen J, Wang B, Huang S, Song M. 2020. The influence of increased population density in China on air pollution. *Sci. Total Environ.* 735:139456
130. Carozzi F, Roth S. 2020. Dirty density: air quality and the density of American cities. *J. Environ. Econ. Manag.* 118:102767
131. Blanco MN, Gassett A, Gould T, Doubleday A, Slager DL, et al. 2022. Characterization of annual average traffic-related air pollution concentrations in the Greater Seattle Area from a year-long mobile monitoring campaign. *Environ. Sci. Technol.* 56(16):11460–72
132. Miller DJ, Actkinson B, Padilla L, Griffin RJ, Moore K, et al. 2020. Characterizing elevated urban air pollutant spatial patterns with mobile monitoring in Houston, Texas. *Environ. Sci. Technol.* 54(4):2133–42
133. Lessler J, Grabowski MK, Grantz KH, Badillo-Goicoechea E, Metcalf CJE, et al. 2021. Household COVID-19 risk and in-person schooling. *Science* 372(6546):1092–97

134. Stevenson M, Thompson J, de Sá TH, Ewing R, Mohan D, et al. 2016. Land use, transport, and population health: estimating the health benefits of compact cities. *Lancet North Am. Ed.* 388(10062):2925–35
135. Ewing R, Park K, Sabouri S, Lyons T, Kim K, et al. 2020. *Reducing vehicle miles traveled (VMT), encouraging walk trips, and facilitating efficient trip chains through polycentric development*. Rep., NITC-RR-1217, Natl. Inst. Transp. Commun., Portland State Univ.
136. Tao T, Wu X, Cao J, Fan Y, Das K, Ramaswami A. 2020. Exploring the nonlinear relationship between the built environment and active travel in the Twin Cities. *J. Plan. Educ. Res.* 43(3):637–52. **https://doi.org/10.1177/0739456X20915765**
137. Jiang Y, Gu P, Chen Y, He D, Mao Q. 2017. Influence of land use and street characteristics on car ownership and use: evidence from Jinan, China. *Transp. Res. D.* 52:518–34
138. Litman TA. 2021. *Understanding transport demands and elasticities: how prices and other factors affect travel behavior*. Rep., Victoria Transp. Policy Inst., Victoria, British Columbia. **https://www.vtpi.org/elasticities.pdf**
139. del Pozo Cruz B, Ahmadi MN, Lee I-M, Stamatakis E. 2022. Prospective associations of daily step counts and intensity with cancer and cardiovascular disease incidence and mortality and all-cause mortality. *JAMA Intern. Med.* 182(11):1139–48
140. Howell NA, Tu JV, Moineddin R, Chu A, Booth GL. 2019. Association between neighborhood walkability and predicted 10-year cardiovascular disease risk: the CANHEART (Cardiovascular Health in Ambulatory Care Research Team) Cohort. *J. Am. Heart Assoc.* 8(21):e013146
141. Pucher J, Buehler R, Bassett DR, Dannenberg AL. 2010. Walking and cycling to health: a comparative analysis of city, state, and international data. *Am. J. Public Health* 100(10):1986–92
142. Glazier RH, Creatore MI, Weyman JT, Fazli G, Matheson FI, et al. 2014. Density, destinations or both? A comparison of measures of walkability in relation to transportation behaviors, obesity and diabetes in Toronto, Canada. *PLOS ONE* 9(1):e85295
143. Buehler R, Pucher J. 2020. The growing gap in pedestrian and cyclist fatality rates between the United States and the United Kingdom, Germany, Denmark, and the Netherlands, 1990–2018. *Transp. Rev.* 41(1):48–72
144. Woodcock J, Edwards P, Tonne C, Armstrong BG, Ashiru O, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet North Am. Ed.* 374(9705):1930–43
145. Singh V, Singh S, Biswal A, Kesarkar AP, Mor S, Ravindra K. 2020. Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. *Environ. Pollut.* 266:115368
146. Berman JD, Ebisu K. 2020. Changes in U.S. air pollution during the COVID-19 pandemic. *Sci. Total Environ.* 739:139864
147. Choma EF, Evans JS, Hammitt JK, Gómez-Ibáñez JA, Spengler JD. 2020. Assessing the health impacts of electric vehicles through air pollution in the United States. *Environ. Int.* 144:106015
148. Dedoussi IC, Eastham SD, Monier E, Barrett SRH. 2020. Premature mortality related to United States cross-state air pollution. *Nature* 578(7794):261–65
149. Anenberg SC, Miller J, Henze DK, Minjares R, Achakulwisut P. 2019. The global burden of transportation tailpipe emissions on air pollution-related mortality in 2010 and 2015. *Environ. Res. Lett* 14(9):094012
150. Hankey S, Lindsey G, Marshall JD. 2017. Population-level exposure to particulate air pollution during active travel: planning for low-exposure, health-promoting cities. *Environ. Health Perspect.* 125(4):527–34
151. Apte JS, Kirchstetter TW, Reich AH, Deshpande SJ, Kaushik G, et al. 2011. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. *Atmos. Environ.* 45(26):4470–80
152. Gillingham KT, Huang P, Buehler C, Peccia J, Gentner DR. 2021. The climate and health benefits from intensive building energy efficiency improvements. *Sci. Adv.* 7(34):eabg0947
153. Wilkinson RG, Pickett K. 2009. *The Spirit Level: Why More Equal Societies Almost Always Do Better*, Vol. 6. London: Allen Lane
154. Thomson H, Thomas S, Sellstrom E, Petticrew M. 2009. The health impacts of housing improvement: a systematic review of intervention studies from 1887 to 2007. *Am. J. Public Health* 99(Suppl. 3):S681–92

155. Milner J, Shrubsole C, Das P, Jones B, Ridley I, et al. 2014. Home energy efficiency and radon related risk of lung cancer: modelling study. *BMJ* 348:f7493
156. Sen S, Khazanovich L. 2021. Limited application of reflective surfaces can mitigate urban heat pollution. *Nat. Commun.* 12(1):3491
157. Wang T, Jiang Z, Zhao B, Gu Y, Liou K-N, et al. 2020. Health co-benefits of achieving sustainable net-zero greenhouse gas emissions in California. *Nat. Sustain.* 3(8):597–605
158. Shindell D, Ru M, Zhang Y, Seltzer K, Faluvegi G, et al. 2021. Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States. *PNAS* 118(46):e2104061118
159. Peters DR, Schnell JL, Kinney PL, Naik V, Horton DE. 2020. Public health and climate benefits and trade-offs of U.S. vehicle electrification. *GeoHealth* 4(10):e2020GH000275
160. Liang X, Zhang S, Wu Y, Xing J, He X, et al. 2019. Air quality and health benefits from fleet electrification in China. *Nat. Sustain.* 2(10):962–71
161. Gan WQ, Davies HW, Koehoorn M, Brauer M. 2012. Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality. *Am. J. Epidemiol.* 175(9):898–906
162. Kaunda RB. 2020. Potential environmental impacts of lithium mining. *J. Energy Nat. Resour. Law* 38(3):237–44
163. Lal RM, Tibrewal K, Venkataraman C, Tong K, Fang A, et al. 2022. Impact of circular, waste-heat reuse pathways on $PM_{2.5}$-air quality, $CO_2$ emissions, and human health in India: comparison with material exchange potential. *Environ. Sci. Technol.* 56(13):9773–83
164. Tian J, Liu W, Lai B, Li X, Chen L. 2014. Study of the performance of eco-industrial park development in China. *J. Clean. Prod.* 64:486–94
165. Kapdan IK, Kargi F. 2006. Bio-hydrogen production from waste materials. *Enzyme Microb. Technol.* 38(5):569–82
166. Megía PJ, Vizcaíno AJ, Calles JA, Carrero A. 2021. Hydrogen production technologies: from fossil fuels toward renewable sources. A mini review. *Energy Fuels* 35(20):16403–15
167. James P, Banay RF, Hart JE, Laden F. 2015. A review of the health benefits of greenness. *Curr. Epidemiol. Rep.* 2(2):131–42
168. Pataki DE, Alberti M, Cadenasso ML, Felson AJ, McDonnell MJ, et al. 2021. The benefits and limits of urban tree planting for environmental and human health. *Front. Ecol. Evol.* 9:603757
169. Aerts R, Honnay O, Van Nieuwenhuyse A. 2018. Biodiversity and human health: mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *Br. Med. Bull.* 127(1):5–22
170. Remme RP, Frumkin H, Guerry AD, King AC, Mandle L, et al. 2021. An ecosystem service perspective on urban nature, physical activity, and health. *PNAS* 118(22):e2018472118
171. Allan K, Phillips AR. 2021. Comparative cradle-to-grave life cycle assessment of low and mid-rise mass timber buildings with equivalent structural steel alternatives. *Sustainability* 13(6):3401
172. Cramm JM, Van Dijk HM, Nieboer AP. 2013. The importance of neighborhood social cohesion and social capital for the well being of older adults in the community. *Gerontologist* 53(1):142–52
173. Gandelman N, Piani G, Ferre Z. 2012. Neighborhood determinants of quality of life. *J. Happiness Stud.* 13(3):547–63
174. Liu Y, Dijst M, Geertman S. 2017. The subjective well-being of older adults in Shanghai: the role of residential environment and individual resources. *Urban Stud.* 54(7):1692–714
175. Menec VH, Nowicki S. 2014. Examining the relationship between communities' 'age-friendliness' and life satisfaction and self-perceived health in rural Manitoba, Canada. *Rural Remote Health* 14(1):159–72
176. Morrison PS. 2011. Local expressions of subjective well-being: the New Zealand experience. *Reg. Stud.* 45(8):1039–58
177. Rehdanz K, Maddison D. 2008. Local environmental quality and life-satisfaction in Germany. *Ecol. Econ.* 64(4):787–97
178. Mouratidis K. 2019. Compact city, urban sprawl, and subjective well-being. *Cities* 92:261–72
179. Dittmann J, Goebel J. 2010. Your house, your car, your education: the socioeconomic situation of the neighborhood and its impact on life satisfaction in Germany. *Soc. Indic. Res.* 96(3):497–513

180. Ettema D, Schekkerman M. 2016. How do spatial characteristics influence well-being and mental health? Comparing the effect of objective and subjective characteristics at different spatial scales. *Travel Behav. Soc.* 5:56–67
181. Ma J, Dong G, Chen Y, Zhang W. 2018. Does satisfactory neighbourhood environment lead to a satisfying life? An investigation of the association between neighbourhood environment and life satisfaction in Beijing. *Cities* 74:229–39
182. Shields MA, Wheatley Price S, Wooden M. 2009. Life satisfaction and the economic and social characteristics of neighbourhoods. *J. Popul. Econ.* 22(2):421–43
183. Fisher KJ, Li F. 2004. A community-based walking trial to improve neighborhood quality of life in older adults: a multilevel analysis. *Ann. Behav. Med.* 28(3):186–94
184. Mueller N, Rojas-Rueda D, Cole-Hunter T, De Nazelle A, Dons E, et al. 2015. Health impact assessment of active transportation: a systematic review. *Prev. Med.* 76:103–14
185. Singleton PA. 2019. Walking (and cycling) to well-being: modal and other determinants of subjective well-being during the commute. *Travel Behav. Soc.* 16:249–61
186. Lu Y, Xiao Y, Ye Y. 2017. Urban density, diversity and design: Is more always better for walking? A study from Hong Kong. *Prev. Med.* 103:S99–103
187. Cao XJ. 2016. How does neighborhood design affect life satisfaction? Evidence from Twin Cities. *Travel Behav. Soc.* 5:68–76
188. Cohen MA. 2008. The effect of crime on life satisfaction. *J. Legal. Stud.* 37(S2):S325–53
189. Cramm JM, Nieboer AP. 2014. Neighborhood attributes security and solidarity promote the well-being of community-dwelling older people in the Netherlands. *Geriatr. Gerontol. Int.* 14(3):681–88
190. Orru K, Orru H, Maasikmets M, Hendrikson R, Ainsaar M. 2016. Well-being and environmental quality: Does pollution affect life satisfaction? *Qual. Life Res.* 25(3):699–705
191. Ruiz C, Hernández-Fernaud E, Rolo-González G, Hernández B. 2019. Neighborhoods' evaluation: influence on well-being variables. *Front. Psychol.* 10:1736
192. Marselle MR, Irvine KN, Lorenzo-Arribas A, Warber SL. 2015. Moving beyond green: exploring the relationship of environment type and indicators of perceived environmental quality on emotional well-being following group walks. *Int. J. Environ. Res. Public Health* 12(1):106–30
193. Oktay D, Rustemli A. 2011. The quality of urban life and neighborhood satisfaction in Famagusta, Northern Cyprus. In *Investigating Quality of Urban Life*, ed. R Marans, R Stimson, pp. 233–49. Dordrecht, Neth.: Springer
194. Vemuri AW, Grove JM, Wilson MA, Burch WR Jr. 2011. A tale of two scales: evaluating the relationship among life satisfaction, social capital, income, and the natural environment at individual and neighborhood levels in metropolitan Baltimore. *Malnutr. Environ. Behav. New Perspect.* 43(1):3–25
195. Coombes E, Jones AP, Hillsdon M. 2010. The relationship of physical activity and overweight to objectively measured green space accessibility and use. *Soc. Sci. Med.* 70(6):816–22
196. Richardson EA, Pearce J, Mitchell R, Kingham S. 2013. Role of physical activity in the relationship between urban green space and health. *Public Health* 127(4):318–24
197. Ambrose G, Das K, Fan Y, Ramaswami A. 2020. Is gardening associated with greater happiness of urban residents? A multi-activity, dynamic assessment in the Twin-Cities region, USA. *Landsc. Urban Plan.* 198:103776
198. Ambrose G, Das K, Fan Y, Ramaswami A. 2023. Comparing happiness associated with household and community gardening: implications for food action planning. *Landsc. Urban Plan.* 230:104593
199. Davis JN, Ventura EE, Cook LT, Gyllenhammer LE, Gatto NM. 2011. LA Sprouts: a gardening, nutrition, and cooking intervention for Latino youth improves diet and reduces obesity. *J. Am. Diet. Assoc.* 111(8):1224–30
200. Kunpeuk W, Spence W, Phulkerd S, Suphanchaimat R, Pitayarangsarit S. 2020. The impact of gardening on nutrition and physical health outcomes: a systematic review and meta-analysis. *Health Promot. Int.* 35(2):397–408
201. Das K, Ramaswami A. 2022. Who gardens and how in urban USA: informing social equity in urban agriculture action plans. *Front. Sustain. Food Syst.* 6:923079
202. Orsini F, Kahane R, Nono-Womdim R, Gianquinto G. 2013. Urban agriculture in the developing world: a review. *Agron. Sustain. Dev.* 33(4):695–720

203. Meerow S, Newell JP, Stults M. 2016. Defining urban resilience: A review. *Landsc. Urban Plan.* 147:38–49
204. Doorn N, Gardoni P, Murphy C. 2019. A multidisciplinary definition and evaluation of resilience: the role of social justice in defining resilience. *Sustain. Resil. Infrastruct.* 4(3):112–23
205. Norris FH, Stevens SP, Pfefferbaum B, Wyche KF, Pfefferbaum RL. 2008. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *Am. J. Commun. Psychol.* 41(1):127–50
206. Birkmann J, Buckle P, Jaeger J, Pelling M, Setiadi N, et al. 2010. Extreme events and disasters: a window of opportunity for change? Analysis of organizational, institutional and political changes, formal and informal responses after mega-disasters. *Nat. Hazards* 55(3):637–55
207. Panteli M, Mancarella P, Trakas DN, Kyriakides E, Hatziargyriou ND. 2017. Metrics and quantification of operational and infrastructure resilience in power systems. *IEEE Trans. Power Syst.* 32(6):4732–42
208. Sun W, Bocchini P, Davison BD. 2020. Resilience metrics and measurement methods for transportation infrastructure: the state of the art. *Sustain. Resil. Infrastruct.* 5(3):168–99
209. Wang L, Xue X, Zhou X. 2020. A new approach for measuring the resilience of transport infrastructure networks. *Complex* 2020:e7952309
210. Turnquist M, Vugrin E. 2013. Design for resilience in infrastructure distribution networks. *Environ. Syst. Decis.* 33(1):104–20
211. Sajjad M, Lin N, Chan JCL. 2020. Spatial heterogeneities of current and future hurricane flood risk along the U.S. Atlantic and Gulf coasts. *Sci. Total Environ.* 713:136704
212. De Sherbinin A, Schiller A, Pulsipher A. 2007. The vulnerability of global cities to climate hazards. *Environ. Urban.* 19(1):39–64
213. Savills. 2022. *Impacts: the future of global real estate*. Issue 5, 2022, London. **https://www.savills.com/impacts/Impacts3_pdfs/SavillsImpacts2022.pdf**
214. Shi L, Moser S. 2021. Transformative climate adaptation in the United States: trends and prospects. *Science* 372(6549):eabc8054
215. McWethy DB, Schoennagel T, Higuera PE, Krawchuk M, Harvey BJ, et al. 2019. Rethinking resilience to wildfire. *Nat. Sustain.* 2(9):797–804
216. Cushman SA, McGarigal K. 2019. Metrics and models for quantifying ecological resilience at landscape scales. *Front. Ecol. Evol.* 7:440
217. Altieri MA, Nicholls CI, Henao A, Lana MA. 2015. Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.* 35(3):869–90
218. Sharifi A. 2019. Resilient urban forms: a macro-scale analysis. *Cities* 85:1–14
219. Brown MA, Soni A. 2019. Expert perceptions of enhancing grid resilience with electric vehicles in the United States. *Energy Res. Soc. Sci.* 57:101241
220. Elmqvist T, Andersson E, Frantzeskaki N, McPhearson T, Olsson P, et al. 2019. Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* 2(4):267–73
221. Sekovski I, Armaroli C, Calabrese L, Mancini F, Stecchi F, Perini L. 2015. Coupling scenarios of urban growth and flood hazards along the Emilia-Romagna coast (Italy). *Nat. Hazards Earth Syst. Sci.* 15(10):2331–46
222. Nasiri NA, Al-Awadhi T, Hereher M, Ahsan R, AlRubkhi AG. 2020. Changing urban ecology a challenge for coastal urban resilience: a study on muscat. *Environ. Urban. ASIA* 11(1):10–28
223. Arup. *Global sponge cities snapshot.* Rep. Arup, London. **https://www.arup.com/perspectives/publications/research/section/global-sponge-cities-snapshot**
224. Duy PN, Chapman L, Tight M, Linh PN, Thuong LV. 2017. Increasing vulnerability to floods in new development areas: evidence from Ho Chi Minh City. *Int. J. Clim. Change Strateg. Manag.* 10(1):197–212
225. Antolini F, Tate E, Dalzell B, Young N, Johnson K, Hawthorne PL. 2020. Flood risk reduction from agricultural best management practices. *J. Am. Water Resour. Assoc.* 56(1):161–79
226. Lim HK, Kain J-H. 2016. Compact cities are complex, intense and diverse but: Can we design such emergent urban properties? *Urban Plan.* 1(1):95–113
227. Taha H. 1997. Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy Build.* 25(2):99–103
228. Ichinose T, Shimodozono K, Hanaki K. 1999. Impact of anthropogenic heat on urban climate in Tokyo. *Atmos. Environ.* 33(24):3897–909

229. Yang B, Yang X, Leung LR, Zhong S, Qian Y, et al. 2019. Modeling the impacts of urbanization on summer thermal comfort: the role of urban land use and anthropogenic heat. *J. Geophys. Res.* 124(13):6681–97
230. Zhao L, Oleson K, Bou-Zeid E, Krayenhoff ES, Bray A, et al. 2021. Global multi-model projections of local urban climates. *Nat. Clim. Change* 11(2):152–57
231. Gunawardena KR, Wells MJ, Kershaw T. 2017. Utilising green and bluespace to mitigate urban heat island intensity. *Sci. Total Environ.* 584–585:1040–55
232. Luo X, Vahmani P, Hong T, Jones A. 2020. City-scale building anthropogenic heating during heat waves. *Atmosphere* 11(11):1206
233. Alhazmi M, Sailor DJ, Anand J. 2022. A new perspective for understanding actual anthropogenic heat emissions from buildings. *Energy Build.* 258:111860
234. Mussetti G, Davin EL, Schwaab J, Acero JA, Ivanchev J, et al. 2022. Do electric vehicles mitigate urban heat? The case of a tropical city. *Front. Environ. Sci.* 10:810342
235. Adelia AS, Ivanchev J, Resende Santos LG, Kayanan DR, Fonseca JA, Nevat I. 2020. *Microscale assessment of the anthropogenic heat mitigation strategies*. Rep., ETH Zurich
236. Yang J, Bou-Zeid E. 2018. Should cities embrace their heat islands as shields from extreme cold? *J. Appl. Meteorol. Climatol.* 57(6):1309–20
237. Feng J, Khan A, Doan Q-V, Gao K, Santamouris M. 2021. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale. *Cell Rep. Phys. Sci.* 2(7):100485
238. Baniassadi A, Sailor DJ, Ban-Weiss GA. 2019. Potential energy and climate benefits of super-cool materials as a rooftop strategy. *Urban Clim.* 29:100495
239. IEA (Intl. Energy Agency). 2020. *Power systems in transition: challenges and opportunities ahead for electricity security*. Rep., IEA, Paris. **https://www.iea.org/reports/power-systems-in-transition**; **https://iea.blob.core.windows.net/assets/cd69028a-da78-4b47-b1bf-7520cdb20d70/Power_systems_in_transition.pdf**
240. Cox SL, Hotchkiss EL, Bilello DE, Watson AC, Holm A. 2017. *Bridging climate change resilience and mitigation in the electricity sector through renewable energy and energy efficiency: emerging climate change and development topics for energy sector transformation*. Rep., NREL/TP-6A20–67040, Natl. Renew. Energy Lab., Golden, CO
241. Dyson M, Li BX. 2020. *Reimagining grid resilience: a framework for addressing catastrophic threats to the US electricity grid in an era of transformational change*. Rep., Basalt, CO: Rocky Mount. Inst.
242. PNNL (Pac. Northwest Natl. Lab.). 2021. *Modeling tomorrow's power grid to enable decarbonization and resilience*. Rep. PNNL-SA-169163. **https://www.pnnl.gov/labobjectives/ModelingForUtilities.pdf**
243. Le Xie CS. 2021. Building a resilient, carbon-neutral electric grid requires energy 'superhighways.' *The Hill*, July 9. **https://thehill.com/opinion/energy-environment/562268-building-a-resilient-carbon-neutral-electric-grid-requires-energy/**
244. Crespo del Granado P, van Nieuwkoop R, Kardakos E, Schaffner C. 2018. Modelling the energy transition: a nexus of energy system and economic models. *Energy Strateg. Rev.* 20:229–35
245. Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, et al. 2014. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. *Energy* 68:1–11
246. Hussain A, Bui V-H, Kim H-M. 2019. Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. *Appl. Energy* 240:56–72
247. Wang Y, Rousis AO, Strbac G. 2020. On microgrids and resilience: a comprehensive review on modeling and operational strategies. *Renewable Sustainable Energy Rev.* 134:110313
248. Lagrange A, de Simón-Martín M, González-Martínez A, Bracco S, Rosales-Asensio E. 2020. Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: an application to a hospital. *Int. J. Electr. Power Energy Syst.* 119:105865
249. Ebadat-Parast M, Nazari MH, Hosseinian SH. 2022. Distribution system resilience enhancement through resilience-oriented optimal scheduling of multi-microgrids considering normal and emergency conditions interlink utilizing multi-objective programming. *Sustain. Cities Soc.* 76:103467
250. Uddin K, Dubarry M, Glick MB. 2018. The viability of vehicle-to-grid operations from a battery technology and policy perspective. *Energy Policy* 113:342–47

251. Feng K, Lin N, Xian S, Chester MV. 2020. Can we evacuate from hurricanes with electric vehicles? *Transp. Res. D.* 86:102458
252. Campbell RJ, Lowry S. 2012. *Weather-related power outages and electric system resiliency*. Rep., Congr. Res. Serv.
253. Parent JR, Meyer TH, Volin JC, Fahey RT, Witharana C. 2019. An analysis of enhanced tree trimming effectiveness on reducing power outages. *J. Environ. Manag.* 241:397–406
254. Barrow CJ. 2012. Biochar: potential for countering land degradation and for improving agriculture. *Appl. Geogr.* 34:21–28
255. Gomez M, Mejia A, Ruddell BL, Rushforth RR. 2021. Supply chain diversity buffers cities against food shocks. *Nature* 595(7866):250–54
256. Parker T, Svantemark M. 2019. Resilience by industrial symbiosis? A discussion on risk, opportunities and challenges for food production in the perspective of the food-energy-water nexus. *Bioremediation* 2(1):7
257. Medina Camarena KS, Wübbelmann T, Förster K. 2022. What is the contribution of urban trees to mitigate pluvial flooding? *Hydrology* 9(6):108
258. Fairchild TP, Bennett WG, Smith G, Day B, Skov MW, et al. 2021. Coastal wetlands mitigate storm flooding and associated costs in estuaries. *Environ. Res. Lett.* 16(7):074034
259. Narayan S, Beck MW, Wilson P, Thomas CJ, Guerrero A, et al. 2017. The value of coastal wetlands for flood damage reduction in the Northeastern USA. *Sci. Rep.* 7:9463
260. Rehak B. 2021. China's "Sponge Cities." *Reduce Flooding – Now!* **https://reduceflooding.com/2021/07/31/chinas-sponge-cities/**
261. Barbour E, Parra D, Awwad Z, González MC. 2018. Community energy storage: A smart choice for the smart grid? *Appl. Energy* 212:489–97
262. Cabiyo B, Fried JS, Collins BM, Stewart W, Wong J, Sanchez DL. 2021. Innovative wood use can enable carbon-beneficial forest management in California. *PNAS* 118(49):e2019073118
263. Braveman P. 2014. What are health disparities and health equity? We need to be clear. *Public Health Rep.* 129:5–8
264. Dempsey N, Bramley G, Power S, Brown C. 2011. The social dimension of sustainable development: defining urban social sustainability. *Sustain. Dev.* 19(5):289–300
265. Tong K, Ramaswami A, Xu C(K), Feiock R, Schmitz P, Ohlsen M. 2021. Measuring social equity in urban energy use and interventions using fine-scale data. *PNAS* 118(24):e2023554118
266. Hughes S, Hoffmann M. 2020. Just urban transitions: toward a research agenda. *WIREs Clim. Change* 11(3):e640
267. Bozeman JF, Nobler E, Nock D. 2022. A path toward systemic equity in life cycle assessment and decision-making: standardizing sociodemographic data practices. *Environ. Eng. Sci.* 39(9):759–69
268. Broto VC, Westman L, Huang P. 2021. Reparative innovation for urban climate adaptation. *J. Br. Acad.* 9(s9):205–18
269. Romero-Lankao P, Nobler E. 2021. *Energy justice: key concepts and metrics relevant to EERE transportation projects*. Rep., NREL/TP-5400-80206, Natl. Renew. Energy Lab.
270. Rawls J. 2020. *A theory of justice: Revised Edition*. Cambridge, MA: Harvard Univ. Press
271. Pandey B, Brelsford C, Seto KC. 2022. Infrastructure inequality is a characteristic of urbanization. *PNAS* 119(15):e2119890119
272. Mahadevia D, Bhatia N, Bhonsale B. 2014. *Slum rehabilitation schemes (SRS) across Ahmedabad: role of an external agency*. CUE Work. Pap. 27, November 2014. **https://cept.ac.in/UserFiles/File/CUE/Working%20Papers/Revised%20New/27CUEWP%2027_Slum%20Rehabilitation%20Schemes%20%28SRS%29%20across%20Ahmedabad%20-%20Role%20of%20an%20External%20Agency.compressed.pdf**
273. Nutkiewicz A, Mastrucci A, Rao ND, Jain RK. 2022. Cool roofs can mitigate cooling energy demand for informal settlement dwellers. *Renew. Sustain. Energy Rev.* 159:112183
274. Census of India. 2011. Census of India. *Census of India 2011*. **https://censusindia.gov.in/census.website**
275. Pandey B, Ramaswami A. 2022. *Quantifying tree cover across all urban areas in India*. Presented at AGU Fall Meet., Chicago, IL, Dec. 12–16. **https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1185671**

276. Metropolitan Council. 2013. *Thrive MSP 2040: status report*. Rep., Metrop. Counc. **https://metrocouncil.org/Council-Meetings/Committees/Land-Use-Advisory-Committee/LandUseAdvCmte/April-18,-2013/Four-Issue-Areas-for-Thrive-MSP-2040.aspx**
277. City of Minneapolis. 2022. Inclusionary zoning requirements. *Community Planning & Economic Development (CPED)*. **https://www2.minneapolismn.gov/government/projects/cped/inclusionary-zoning/**
278. Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, et al. 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* 16(7):073005
279. DOE (Dep. Energy). 2021. Energy Justice Dashboard (Beta). *Office of Economic Impact and Diversity*. **https://www.energy.gov/diversity/energy-justice-dashboard-beta**
280. Vega-Perkins J, Newell JP, Keoleian G. 2023. Mapping electric vehicle impacts: greenhouse gas emissions, fuel costs, and energy justice in the United States. *Environ. Res. Lett.* 18(1):014027
281. Schwarz K, Fragkias M, Boone CG, Zhou W, McHale M, et al. 2015. Trees grow on money: urban tree canopy cover and environmental justice. *PLOS ONE* 10(4):e0122051. **https://doi.org/10.1371/journal.pone.0122051**
282. Riedman E, Roman LA, Pearsall H, Maslin M, Ifill T, Dentice D. 2022. Why don't people plant trees? Uncovering barriers to participation in urban tree planting initiatives. *Urban For. Urban Green.* 73:127597
283. Conway TM, Yuan AY, Roman LA, Heckert M, Pearsall H, et al. 2022. Who participates in green infrastructure initiatives and why? Comparing participants and non-participants in Philadelphia's GI programs. *J. Environ. Policy Plan.* 25(3):327–41. **https://doi.org/10.1080/1523908X.2022.2128310**
284. Rothfusz LP. 1990. *The heat index "equation" (or, more than you ever wanted to know about heat index)*. NWS Tech. Attach. SR 90-23, Fort Worth, TX. **http://www.srh.noaa.gov/images/ffc/pdf/ta_htindx.PDF**
285. Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, et al. 2007. *Ranking of the world's cities most exposed to coastal flooding today and in the future*. Exec. Summ. OECD. **https://www.oecd.org/env/cc/39721444.pdf**
286. UNDESA (U.N. Dept. Econ. Soc. Aff.). 2018. World Urbanization Prospects 2018. *United Nations Department of Economic and Social Affairs, Population Dynamics*. **https://population.un.org/wup/Download/**
287. Gallup Inc. 2009. Understanding how Gallup uses the Cantril Scale. *Gallup.com*. **https://news.gallup.com/poll/122453/Understanding-Gallup-Uses-Cantril-Scale.aspx**.
288. Climate Watch. 2022. Climate Watch historical GHG emissions. *World Resources Institute*. **https://www.climatewatchdata.org/ghg-emissions**
289. Ritchie H, Roser M, Rosado P. 2020. $CO_2$ and greenhouse gas emissions. *OurWorldInData.org*. **https://ourworldindata.org/co2-and-greenhouse-gas-emissions**
290. Hasanbeigi A. 2021. Global cement industry's GHG emissions. *Global Efficiency Intelligence*. **https://www.globalefficiencyintel.com/new-blog/2021/global-cement-industry-ghg-emissions**
291. FAO (Food Agricul. Org. U.N.). 2023. QUASTAT. FAO's Global Information System on Water and Agriculture. *Food and Agriculture Organization of the United Nations*. **https://tableau.apps.fao.org/views/ReviewDashboard-v1/country_dashboard?%3Adisplay_count=n&%3Aembed=y&%3AisGuestRedirectFromVizportal=y&%3Aorigin=viz_share_link&%3AshowAppBanner=false&%3AshowVizHome=n**
292. Pomponi F, Stephan A. 2021. Water, energy, and carbon dioxide footprints of the construction sector: a case study on developed and developing economies. *Water Res.* 194:116935
293. IHME (Inst. Health Metr. Eval.). 2019. Global Burden of Disease Study 2019. Results. *Institute for Health Metrics and Evaluation*. **http://ghdx.healthdata.org/gbd-results-tool**
294. World Health Organization (WHO). 2018. *Global status report on road safety 2018*. World Health Organization, Geneva