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Mainstreaming the local climate zone framework for climate-resilient cities

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The local climate zone framework is valuable for building climate-resilient cities but is limited in application. This limitation can be resolved by addressing three aspects: transdisciplinary dialog, global atlas construction, and cost–benefit assessment.

At the Ministerial Meeting(s) on Urbanization and Climate Change, the Conference of the Parties at its twenty-ninth meeting emphasized the promotion of climate-resilient cities through multilevel action[1]. Adapting an urban landscape system can facilitate the basic analysis of local climate response and implementation of adaptation policies for building climate-resilient cities. Stewart and Oke proposed the local climate zone (LCZ) framework, combining surface structure (height and spacing of buildings and vegetation), cover (permeable or impermeable) and human activity attributes that influence screen height temperatures (Fig. 1a), spanning hundreds of meters to several kilometers[2]. The LCZ framework focuses on landscape-induced environmental effects and has been adopted in research on urban heat islands, heat waves, air pollution, and energy balance[3,4]. After more than 10 years of development, the effectiveness of this framework in the urban climate domain has been validated in over 280 cities worldwide (Fig. 1b, c). Indeed, several cities, including Colombo, Sri Lanka; Toulouse, France; and Szeged and Novi Sad, Hungary, have adopted LCZ-based urban planning. Meanwhile, global and regional urban climate research projects, such as MapUCE and ENLIGHT, apply LCZ as a optional base for urban landscapes[4]. Mainstreaming the LCZ framework can facilitate the sharing and comparative analysis of experiences among cities and support globally harmonized climate-resilient urban development.

Building climate-resilient cities follows the "climate monitoring–risk assessment–social adaptation–spatial transformation" practice model. However, applied research on the LCZ framework focuses on monitoring climate dynamics and risk assessment. Herein, we identify the key challenges in translating LCZ-based urban climate knowledge into social adaptation and spatial transformation. We propose steps for mainstreaming the LCZ framework as a landscape model for climate-resilient city planning.

Key challenges in mainstreaming the LCZ framework

Transforming climate knowledge into resilience policy. Numerical analysis and spatial modeling of urban climate based on LCZ provide fundamental knowledge support for building climate-resilient cities. However, the adaptive transformation system is an institutional spatial planning tool for transforming natural and anthropogenic spaces developed under socio-economic functions oriented to production, health, and safety. By contrast, the behavior of standardized urban climate monitoring based on LCZ typically focuses on micro and local scales and is regarded as an episodic natural phenomenon with a high degree of heterogeneity[5]. Moreover, the economic, social, and policy aspects of the LCZ discourse have not been comprehensively integrated with climate resilience[6]. Spatially, existing LCZ-related research focusing on the boundary fitness of the study scale to the adaptive transformation unit is rarely discussed. Related research focuses on localized climate boundaries without administrative boundaries, raising issues of resource allocation and cross-regional cooperation. These mismatches in disciplinary language, research paradigms, and values present a key challenge in mainstreaming the LCZ framework and translating climate knowledge into resilience policy.

Converting urban climate research into transferable global knowledge. Global knowledge sharing can reduce the time and economic costs of building climate-resilient cities. Certain LCZ types are rare or missing in certain cities, leading to urban climate discoveries for which reliability and generalizability are not guaranteed. For example, the high heat hazard in the Beijing and Cairo metropolitan area is 94.26%, and 31.49%, respectively, despite both populated areas being compact-type LCZs[7]. This finding can be attributed to Cairo's natural LCZ, primarily bare soil, and its thermal response pattern, which differs significantly from Beijing's (for which the LCZ is primarily low vegetation)[7]. Consequently, LCZ should evolve beyond single-city case studies to encompass comparative analyses across multiple cities, ultimately enabling global-scale assessments. For example, Taubenböck et al. applied the LCZ framework to classify 110 cities worldwide into seven types based on morphology and spatial configuration, potentially leading to different thermal environmental responses[8]. Furthermore, a surface urban heat island (UHI) analysis of 50 cities worldwide, conducted by Bechtel et al., found that LCZ1 compact high-rise built-up areas embedded in waterfront areas exhibit contrasting surface UHI characteristics when compared to those within high-density commercial areas[9].

Effective knowledge sharing is reflected by broadening the depth of the LCZ framework. The construction of future climate-resilient cities is generally oriented toward urban regeneration without marked shifts in local spatial scenarios. The LCZ framework currently applied contains 17 standard types, failing to sufficiently address the modeling needs of adaptive transformation. For example, the common adaptation strategy of increasing greening in high-density built-up areas is often described by a shift from compact-type LCZs (high building density) to open-type LCZs (low building density). However, only the surface cover changes during this process, while the buildings remain unchanged. Consequently, the simulation effects of the strategies in this LCZ framework reduce their robustness due to missing classes.

Integrating climate effects into sustainability-oriented cost-benefit analyses. Building climate-resilient cities requires balancing costs and

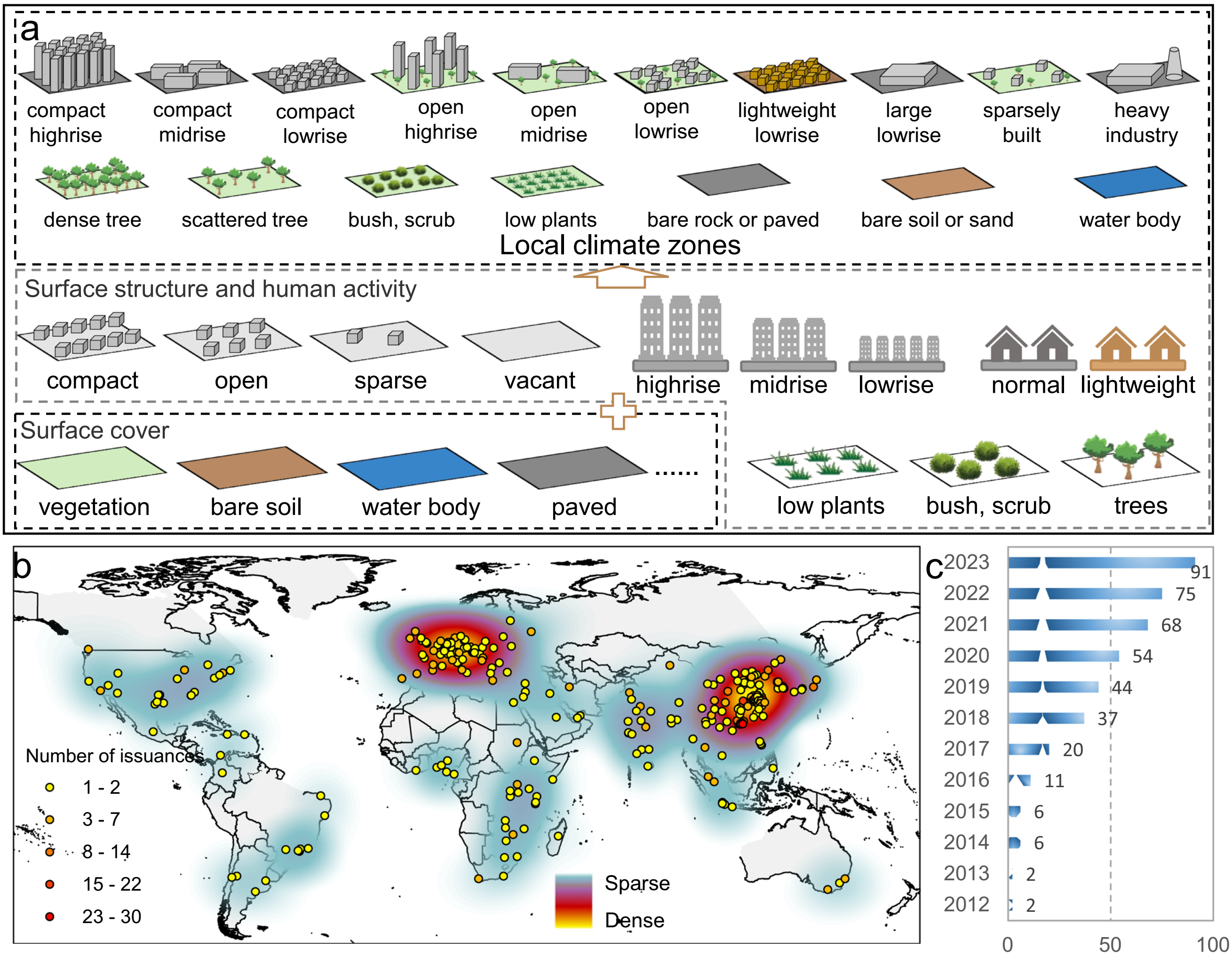

Fig. 1 | Definition of LCZ and spatiotemporal distribution of LCZ studies. a The essence of LCZ is a combination of surface structure, cover and human activity. Surface structure describes the height and spacing of buildings and trees, such as the density of buildings (compact, open, sparse, vacant), the height of buildings (high-rise, mid-rise, low-rise), fabric (heavy, lightweight), and the type of vegetation (trees, shrubs, or low-growth), and affects the local climate by altering the balance of air currents, heat transport through the atmosphere, and short-wave and long-wave radiation. Surface cover describes the albedo, moisture supply, and heating/cooling potential of the ground, e.g., vegetative cover, bare soil, bodies of water, paved surfaces, snow, wetlands, etc. Human activity describes the differences in anthropogenic heat emissions, such as those from heavy industry, residential, and commercial. After going through their combinations and eliminating some unlikely classes, 17 standard LCZ classes were identified. **b** This figure shows the spatial distribution of LCZ research from 2012 to 2023, with LCZ studies being conducted in most regions of the world. Spatially, two hotspot research regions have been formed, namely East Asia and Europe, while fewer studies have been conducted in Latin America, Africa, and Oceania. **c** This figure shows the trend in the number of papers published in LCZ studies between 2012 and 2023. The number of studies related to the LCZ continues to increase, with the highest number of studies at 91 in 2023.

benefits, but most studies focus solely on the climate effects of adaptive transformation. Yang et al. assessed optimal landscape configuration solutions for two large cities in Northeast China[10,11]. They reported that open built-up areas can reduce the average UHI intensity in Dalian from 12.5 °C to 11.7 °C and decrease the heat vulnerability index in Shenyang by 14.85%. Meanwhile, in Nagpur, India, the LCZ framework has been applied to model the differential effects of cooling strategies in different neighborhoods. Measures to increase green space are more effective in LCZ 3_F (0.8 °C) and LCZ 9 (2.7 °C)[12]. However, these solutions focus exclusively on climate improvement effects without assessing associated implementation costs and benefits of the related synergies, or the feasibility of the solutions. Consequently, developing an integrated, multi-objective cost–benefit assessment system is essential for the sustainable and feasible adaptive transformation needed to mainstream LCZs.

Call for actions for mainstreaming the LCZ framework

Mobilizing transdisciplinary dialogue to translate climate knowledge. Transforming climate knowledge into resilience policies requires the unit boundaries of the LCZ to be aligned with the adaptive transformation units, revealing the stakeholders for LCZ adaptation and transformation. The basic units of adaptive transformation are divided according to their functions or community attributes. The stakeholders within the unit, with the authority to make decisions regarding the current management and future development of the unit, are known. In climate monitoring and risk assessment, mainstreaming the LCZ framework necessitates alignment of the research scale with the functional or community units to avoid resource allocation and cross-regional cooperation issues. Based on the local climate consistency attribute of LCZ, the interpretability of landscape units to local climate should be demonstrated by emphasizing the social value of the local climate to compensate for the differences in climate perception among different disciplines. For example, the LCZ framework can be applied to identify and protect vulnerable populations by analyzing differences in the impact of climate risks on different groups. Additionally, an urban climate prediction model with controllable variables can be developed to facilitate the monitoring and prediction of high-risk periods in the local climate. Constructing a multi-factor impact layer for climate risks can facilitate identifying and managing high-climate-risk areas.

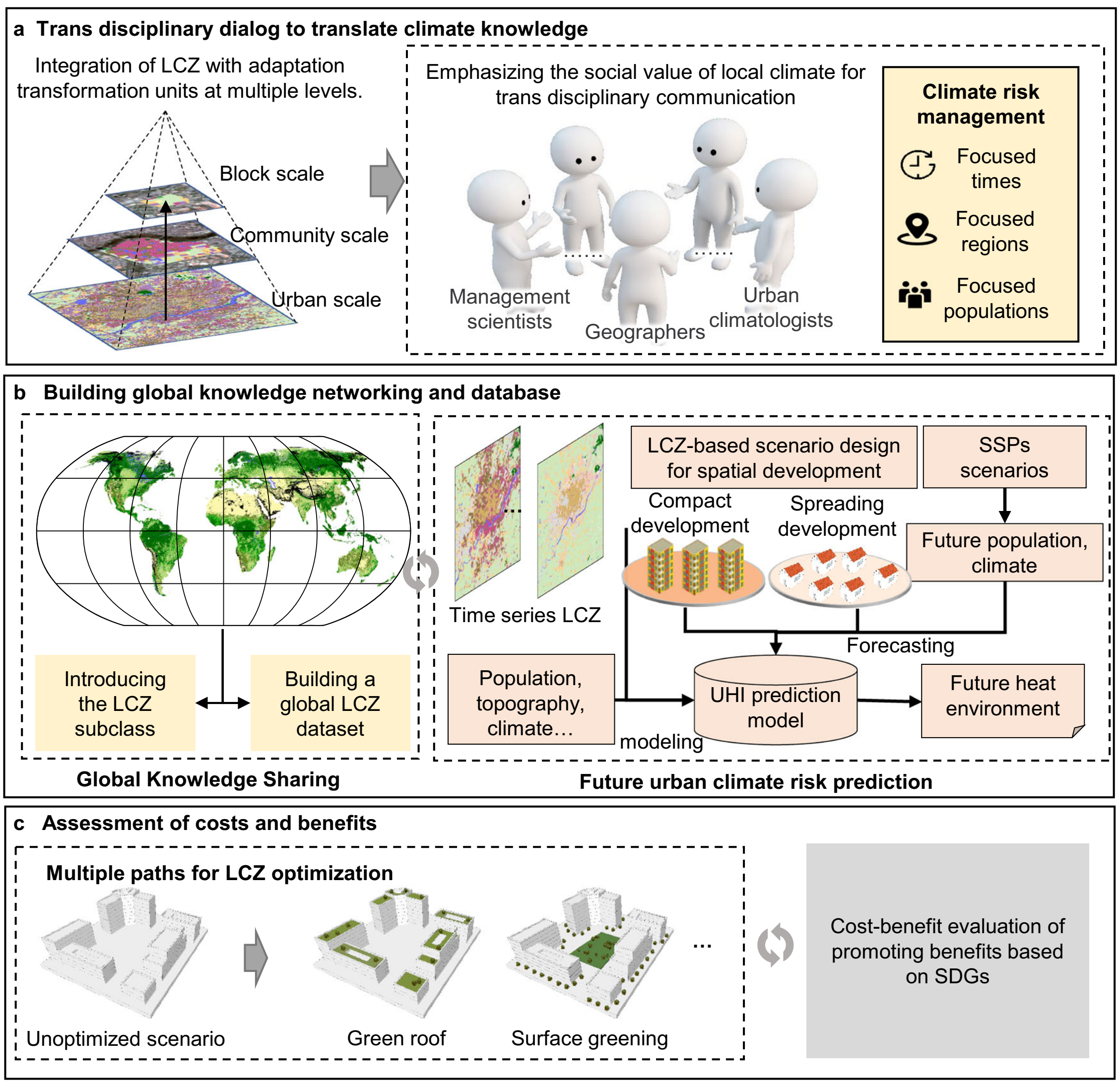

Fig. 2 | Actions to mainstream the LCZ framework into climate-resilient city building. a LCZ acts as a crucial bridge between climate knowledge and resilience policies by aligning with adaptation and transformation units at the block, community, and urban levels. LCZ helps identify vulnerable groups and enables the development of controllable urban climate prediction models. It also allows for constructing multi-factor climate risk impact layers, pinpointing and managing high-risk areas. **b** LCZ serves as a consistent landscape standard for global urban climate analysis and modeling through a worldwide dataset (global LCZ maps adapted from Demuzere et al.[15]). Complementing LCZ with information on urban buildings improves classification accuracy. The introduction of multi-parent LCZ subclasses reflects local climate optimization from minor built-up pattern adjustments. Combining greenhouse gas emission scenarios with LCZ-based adaptation solutions provides global foresight, making climate-resilient city building more cost-effective in emerging cities. **c** LCZ is evaluated with a comprehensive, quantifiable index system covering economic, technical, and social aspects. LCZ-based adaptive transformation solutions must be economically feasible, technically sound, and socially acceptable. For instance, the cost–benefit assessment of adapting LCZ units can be evaluated in terms of monetizing the degree of sustainable development goals (SDGs) advancement..

Building global knowledge, networking, and databases. Cities and climate risks are dynamic, necessitating knowledge sharing and forecasting future global urban climates under different development scenarios. A global LCZ dataset can provide a consistent landscape standard for urban climate analysis and modeling. Indeed, the global LCZ dataset initially established by the World Urban Database and Access Portal Tool Project has greatly facilitated knowledge sharing[13]. However, the dataset's accuracy in classifying built-type LCZs varies from 50% to 78%, failing to satisfy high-precision urban climate modeling requirements and necessitating supplementation with contextual and elemental information related to urban buildings.

Moreover, multi-parent LCZ subclasses must be introduced into climate simulations to reflect the local climate optimization effects of micro-adjustments to existing built-up patterns[1]. For example, adding trees (LCZ B) to a high-density mid-rise complex (LCZ 2) elevates it to the $LCZ2_B$ subclass. Additionally, controls for macro impacts of contextual information, such as climate type, latitude, longitude, and elevation, on urban climate must be implemented. Combining greenhouse gas emission scenarios with adaptive transformation solutions to provide global foresight into the climate response of cities can economize the construction of climate-resilient cities.

Global knowledge networks and databases should also guide the selection of climate adaptation pathways for cities at different stages of development. For small cities and under-resourced areas, low-cost adaptation strategies should be prioritized. These strategies should emphasize simulating the land use game between built and natural types of LCZs that emerge through urban expansion and development. By contrast, within large and developed cities, comprehensive adaptation strategies for long-term climate risks should be prioritized. This process involves evaluating the impacts of high-cost adaptation measures, such as greening or cooling of built-up LCZs and the development of urban parks, which are primarily driven by urban renewal initiatives.

Enabling informed cost-benefit decisions for widespread adoption of the LCZ framework. The LCZ has similar built-up landscapes and local climatic attributes, providing a reference point for the cost–benefit assessment at a specific regional scale. Thus, employing LCZ as the basic unit for cost–benefit evaluation aids in generalizing the assessment results. We suggest combining cost-effectiveness with global universal and systematic indicator systems to enhance comparability. For instance, the cost–benefit assessment of adapting LCZ units can be evaluated in terms of monetizing the degree of sustainable development goals (SDGs) advancement[14]. Specifically, the costs and benefits can be categorized into the costs of inaction and the costs and benefits associated with taking action. The costs of inaction reflect the monetized outcomes of SDG achievements without implementing adaptation measures. By contrast, adaptation costs represent the monetized expenses related to the construction, operation, and maintenance of an adaptation program. Adaptation benefits are the monetized results indicating the level of SDGs achieved by implementing adaptation measures.

To monetize the achievement of the SDGs, various models must be utilized. For environmental benefits, measuring the progress of SDG 13 (Climate Action) requires evaluating the value of carbon emission reductions. When assessing societal benefits, the impact of SDG 3 (Good Health and Well-Being) can be estimated by discounting economic losses from reduced productivity owing to heat stress, employing the productivity loss method. Moreover, the advancement of SDG 11 (Sustainable Cities and Communities) can be estimated by assessing the decrease in energy consumption for air conditioning using the energy savings method. Regarding economic benefits, the progress of SDG 9 (Industry, Innovation, and Infrastructure) can be monitored through input–output modeling to trace the cascading effects of climate investments and to compute the number of direct and indirect jobs generated per million invested, among other metrics. A graphical representation of the three actions to mainstream the LCZ framework mainstreaming is provided in Fig. 2.

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J.Y. designed the study. W.Y. interpreted the data and wrote the paper. A.B., B.H., and Q.G. gave technical support and conceptual advice.

Competing interests
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