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Urban sustainability: challenges and opportunities for resilient and resource-efficient cities

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1. Introduction

Urban systems were previously understood as representations of dissipative systems, where people could only survive as long as cities were a center for the inflow of food, fuel, and other goods that send out products and waste (Nicolis and Prigogine, 1977). This outdated view of cities as merely centers for resource inflow and waste disposal has evolved, as it has been realized that the capacity for ecological and social regeneration is under threat. The biophysical limits to growth, as initially discussed by Meadows et al. (1972), have come to be recognized as fundamental elements for sustaining development within the biosphere (Rees and Wackernagel, 1996; Lovelock, 2000; Odum and Odum, 2001), including urbanized areas, as represented by the stock of natural capital and rural zones in Figure 1. However, most geopolitics continues to drive the consumption of resources with the highest potential and the lowest possible cost, ignoring borders and negative externalities (Roberts et al., 2016). Therefore, it is necessary to move beyond neoclassical economics and develop a critical ecological economics, as argued by Georgescu-Roegen (1971), Martinez-Alier (1987), and Daly and Townsend (1993), among others. In this process, human economic systems should be viewed under an integrated and inclusive perspective to plan the use of geographical space and time (Akenji et al., 2021).

Economic growth, historically driven by capital accumulation, has led to environmental degradation and increasingly fails to translate into improved quality of life as the natural environment deteriorates (Hirvilammi, 2020). Especially since 2008, the application of this management mentality generated wealth only for shrinking segments of society, usually resulting in inequalities and increasing social problems and basic human needs. However, the increase in monetary wealth no longer translates into an improvement in quality of life simply because such development is impossible in a rapidly degrading natural environment (Marques, 2020). Nature has been the main collateral victim of capitalism's desperate struggle against crises, recessions, and the decline of growth rates. Therefore, the inevitable consequence of this process of intensified degradation of the natural environment is the growing divergence between GDP growth and other indices that measure the increase in human wellbeing (Odum and Odum, 2001; Capra, 2004; Aguilar-Rivera, 2021).

In this context, cities are complex ecosystems and centers for ideas, public space, trade, culture, science, productivity, and social development. As symbolized by the red color flows in Figure 1, cities are highly dependent on large amounts of resources and, equally, generate large amounts of by-products to support urban lifestyles, which requires careful attention. Cities not only consume energy and produce pollution but also serve as catalysts for new

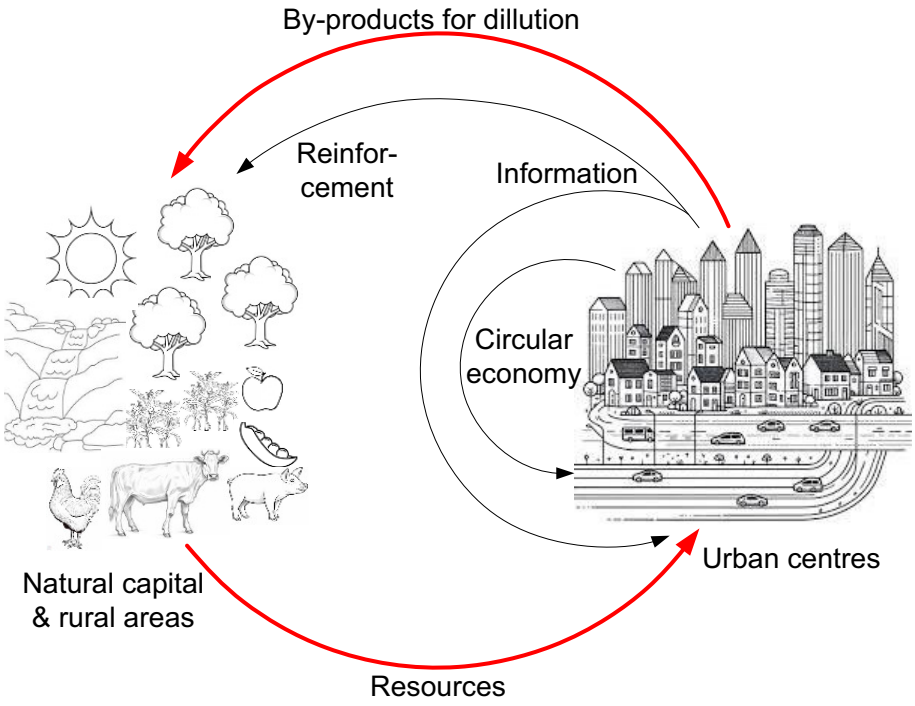

FIGURE 1
The relationship between natural capital, rural areas and urban centers.

market dynamics, labor restructuring, conflicts, the development of governance tools and strategies, increased demand for community services, and the eventual transformation or decline of established cultural and social models, sometimes replaced by new ones or, in the worst case, by nothing at all (Ulgiati and Zucaro, 2019).

In 2022, 56% of the world's population resided in urban areas, and by 2050, 70% of the world's population is projected to live in urban areas (United Nations, 2024). As the world continues to urbanize, sustainable development increasingly depends on successful *Urban Resource Management*. Therefore, alongside various cultural and psychological factors, biophysical needs—including food, housing, transportation, drinking water, sanitation, sewage systems, electricity and gas distribution, urban transport, environmental regulation, employment, and essential services like education and primary healthcare—will pose significant challenges for many countries in addressing the needs of expanding urban populations (UN Habitat United Nations Human Settlements Programme, 2024). During times of decreasing natural resource availability, implementing more resilient and adaptable resource supply systems—such as diverse energy conversion technologies (e.g., thermal and photovoltaic solar panels, fuel cells, and decentralized cogeneration of electricity)—along with changes in lifestyle and local consumption and production patterns could lay the groundwork for a less resource-intensive urban lifestyle. As Schumacher (1989) argued, "small is beautiful". The driver of sustainability lies in a fair and just transition, assessing the resource metabolism of an urban system.

2. Challenges and opportunities for sustainable cities from a *Resource Management* perspective

To achieve more sustainable urban cities, a fundamental aspect is to understand how cities function from a systemic perspective, viewed as an open system that exchanges energy and materials with the external environment that sustains it. For this ultimate goal, it is both urgent and essential to address these challenges, among others posed by rapid urbanization:

- How can we accurately measure the direct and indirect flows of resources in urban systems?
- How can we efficiently manage the environmental impacts caused by supply chains?
- How can we prepare for the inevitable scarcity of resources amid growing demand for goods and services in urban systems?

Cities, as hubs of consumption and production, require integrated strategies to manage their resource needs and environmental impacts (Figure 1). Achieving sustainable cities requires a comprehensive redesign, effective *Resource Management*, positive reinforcement feedback to natural and rural areas (Odum, 1996), and continuous monitoring, with an emphasis on environmental, social, and economic impacts. For this reason, the United Nations included cities and communities in the 17 Sustainable Development Goals (SDGs) within the 2030

Agenda (Sachs et al., 2024; UN-SDGs, 2019), highlighting Goal 11: "Make cities inclusive, safe, resilient, and sustainable". The prerequisites for a sustainable city include ensuring current and future wellbeing, minimizing environmental impacts, promoting participatory governance to develop effective solutions, and conserving resources for future generations.

Focused on sustainable urban systems and resource management, the *Urban Resource Management* approach must address the interconnections between sustainable development and urban systems in order to achieve a sound design of urban metabolism. As shown in Figure 1, key elements for a sustainable urban metabolism include the availability and quality of resources within urban systems—such as food supply, housing, transportation, commerce, health, and air and water quality—along with those outside the system, like agricultural and industrial production, waste management, surface and groundwater health, landscape, and surrounding ecosystems. These factors define both opportunities and limitations for further development and wellbeing. At this point, selecting appropriate methods for identifying and quantifying these features and supporting discussion is a fundamental aspect, with a focus on different scales for analysis. However, as discussed by Giannetti et al. (2020), systemic approaches seem to be more appropriate for such purposes.

Among others, an important operational tool being used to boost a city's SDG achievement is the framework for sister city partnerships, which allows international municipal cooperation (Atanga et al., 2024). Initiatives in areas such as water and sanitation, education, healthcare, culture, environmental sustainability, recreation, and local economic development are examples of how international municipal cooperation can accelerate the achievement of the 2030 Agenda for cities. Another fundamental concept for more sustainable cities is the Circular Economy (CE), since it aims to keep a given material or energy within the anthropogenic system for as long as possible before discarding it. Ensuring a successful transition to a circular economy requires a holistic evaluation of sustainability across various periods, geographical scales, and multiple dimensions. It is widely acknowledged that there is a direct relationship between environmental preservation and economic growth. Economic regeneration policies, in which consumption behaviors and expenditures are linked to a fundamental shift in the economic structure toward consumption-driven services, are essential for the successful implementation of circular models (Genovese and Pansera, 2020).

Still considering current innovations and new scientific findings, the Internet of Things (IoT) is another approach that has been utilized to introduce innovative solutions and practical applications aimed at reducing environmental burdens and preserving natural capital. Smart cities represent one of this century's transformative initiatives, aimed at converting traditional cities into automated, reliable, well-planned, and intelligent urban environments (Abu-Rayash and Dincer, 2025). In order to potentially achieve a well-designed smart city, it is crucial to establish innovative socio-multidisciplinary conceptual models, actions, and strategies to ensure the sustainable management and appropriate allocation of resources, as well as the development of environmentally sustainable economies (Kou et al., 2024; Zucaro et al., 2022). On the other hand, we must be aware that being smart does not necessarily mean being sustainable (Pierucci et al., 2024).

Urban citizens' wellbeing, also referred to as city livability, depends on creating conditions that enable citizens to thrive and enjoy a high quality of life. Key factors influencing this include the availability and fair distribution of resources, individual perceptions, community organization and conditions (such as education levels, public services, leisure time, and access to green spaces), environmental awareness, and social and economic development. These elements are deeply interconnected and play a crucial role in shaping a city's metabolism. Although there is still room for discussion, the sustainability and wellbeing of urban areas have been examined by the scientific community (del Mar Martínez-Bravo et al., 2019) and in policy discussions (United Nations, 2022), emphasizing the critical interplay between urban growth, the exploitation of natural resources (including non-renewable energy and materials), and their environmental impacts. Aspects that can be considered intangible, such as political ideology, the academic background of decision-makers, access to natural resources, and religion, among others (Agostinho et al., 2021), also need to be better evaluated, as they could lead to decisions that make cities more sustainable.

In summary, achieving sustainable urban systems requires an integrated approach that addresses the complex interactions between resource management, ecological balance, and social wellbeing. Policymakers must prioritize strategies that promote the efficient use of resources, foster circular economies, and enhance resilience against environmental challenges such as climate change and resource depletion. Key actions should include

- Implementing sustainable urban planning that optimizes resource flow and minimizes waste
- Investing in innovative technologies such as renewable energy, waste-to-resource systems, and smart city infrastructure
- Promoting participatory governance, engaging citizens and local communities in decision-making processes to ensure that development aligns with social and environmental needs
- Strengthening international cooperation between cities through frameworks like sister city partnerships, which can accelerate the achievement of the SDGs.

By focusing on these areas, cities can transform into resilient, resource-efficient environments that not only meet the needs of their growing populations but also ensure the wellbeing of future generations. We believe the Urban Resource Management section of *Frontiers in Sustainable Cities* is a key platform for advancing sustainable urban practices, especially from a biophysical perspective. We welcome submissions focused on addressing the grand challenges involved in achieving more sustainable urban environments, whether through theoretical discussions or the application of methods to better understand how cities operate and how they can increase their resilience to current issues that directly affect their functionality (e.g., global warming, water scarcity, food insecurity, or domestic or international conflicts). However, innovative approaches beyond those challenges are also welcome, as long as they are scientifically grounded and make an original contribution to the advancement of the field. The path to sustainability is complex, but it is essential

for building cities that are inclusive, safe, and environmentally just. The journey starts with informed decisions and bold actions. We invite you to join us on this journey!

Author contributions

AZ: Conceptualization, Writing – original draft, Writing – review & editing. FA: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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