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REVIEW ARTICLE

Thermodynamic-based ecological scaling theory in urban metabolic framework: a review

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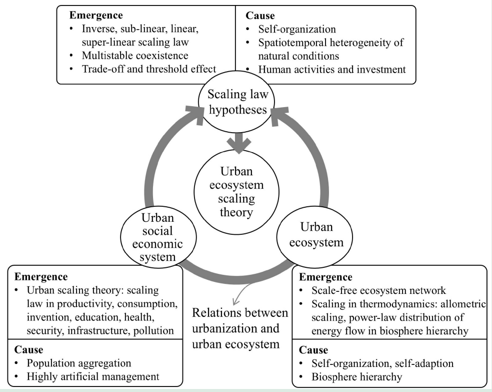
HIGHLIGHTS

- Under thermodynamic, urban ecosystem fits scaling law due to self-organization.
- Urban ecosystem has similar scaling to social economic system.
- The scaling law transitions are reflected in the multistable coexistence.



ABSTRACT: Prior research has consistently demonstrated that urban economic and social systems adhere to the empirical scaling law. Furthermore, a plethora of evidence, including the scale-free networks of energy metabolism, the allometric growth patterns of species and populations, and the scaling law relationship between exergy and transformity in biosphere systems across various levels, indicates that urban ecosystems exhibit multi-level scaling law characteristics in energy metabolism under self-organization, alongside significant human activity imprints. This study synthesizes these findings to hypothesize that urban ecological components are also aligned with system-level scaling theory within the urban metabolism framework. This encompasses: 1) the existence of multistable coexistence and mutual transformation phenomena, mirroring the dynamic nature of scaling laws; and 2) a nuanced balance between the ecosystem and the socio-economic system, particularly in the realms of spatial competition and output efficiency. The ecosystem scaling theory hypotheses of urban metabolic processes offer a theoretical foundation for identifying ecological security tipping points, which are pivotal in the strategic decision-making for ecological planning and management in the future.

KEYWORDS: Ecosystem scaling theory, Urban metabolism, Complexity, Critical review

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1 Introduction

Existing complexity studies generally interpret urbanization as a gradual increase in the proportion of people residing in urban areas. Urbanization triggers transformations in economic expansion, population concentration, social advancement, and spatial reorganization (Gu, 2019; Meng et al., 2021; Meng and Long, 2022). Within this context, the urban economy and population agglomeration exhibit a spatially consistent scaling law, which laid the groundwork for the early development of "scaling theory". This theory encompasses multiple scaling relationships involving urban population, built upon environment, socioeconomic output, and infrastructure costs (Bettencourt, 2013; West, 2018). The implications of this theory extend to the sprawl and contraction dynamics of cities, encompassing natural population growth, mobility shifts, labor division, economic benefits across sectors, and improvements or decommissioning of infrastructure (Alves et al., 2016). Rather than linear changes in the conventional sense, this law consistently manifests log-linear correlations—a phenomenon known as the "urban scaling law" (Bettencourt, 2013). Moreover, the scaling law exhibits super- or sub-linear characteristics, depending on whether the scaling coefficient exceeds 1 (or falls below 1). The super-linear and sub-linear scaling laws articulate that certain system indicators do not adhere to a 1:1 scaling ratio. Super-linear scaling occurs when specific indicators increase at a rate greater than the population growth, signifying those elements such as information innovation, wealth, and resources experience augmented benefits proportion more than the rising population sizes. Conversely, sub-linear scaling is observed when indicators increase at a rate less than the population growth, typically reflecting strategies aimed at internal optimization and enhancing efficiency as the population expands.

Bettencourt (2013) developed a suite of scaling law models to forecast urban land use dynamics, infrastructural network evolution, human interaction intensity, energy consumption, and other key indicators in cities. Drawing on data from thousands of cities, these models affirm the universal applicability of scaling laws to urban systems. For instance, during urban expansion, the physical and functional aspects of cities tend to converge, displaying distinct scaling laws amidst spatial competition. Economic growth and the labor market exhibit super-linear scaling (Batty, 2008; Sugar and Kennedy, 2021), with social volume per capita (e.g., per capita wage or the number of new inventions) increasing with city size, whereas infrastructures (e.g., traffic networks) exhibit sub-linear growth, with per capita urban infrastructure occupying less building volume (Bettencourt, 2013; Keuschnigg et al., 2019; Sugar and Kennedy, 2021). The urban scaling law has become instrumental in predicting social progress and challenges, encompassing education, employment, innovation, health, and crime (Table 1) (Bettencourt et al., 2007; Gomez-Lievano et al., 2017; Bilal et al., 2021; Lu et al., 2024). For example, Bilal et al. (2021) observed the population mortality in cities in the United States and 10 countries in Latin American and found that population mortality shows a sub-linear drive in cities of the United States, with lower mortality in large cities, whereas population mortality in Latin American cities exhibits a super-linear drive. Additionally, recent research indicates that urban waste generation globally adheres to scaling laws (Lu et al., 2024). This research finds out that wastewater generation, municipal solid waste, and greenhouse gas emissions have super-linearly, linearly, and sub-linearly scaling relationships with city size, respectively, in the worldwide urban system.

Zipf's law, a pivotal branch of scaling theory, offers an empirical perspective that suggests a Pareto distribution can represent city size distribution and ranking, with the shape parameter, known as the Pareto index, typically close to 1 (Arshad et al., 2018). Initially identified by Auerbach (1913) and subsequently refined by Singer (1936) and Zipf (1949), this law has become a cornerstone in urban size research (Arshad et al., 2018; Wan et al., 2020). It reveals a log-linear inverse correlation between resource quality and quantity, encompassing renewable energy to human information, applicable at both national and individual scales (Liu et al., 2021). Based on congruent growth dynamics and spatial attractiveness, empirical evidence from Li et al. (2017) demonstrates the presence of a consistent scaling law relationship among socioeconomic interactions, road networks, and population size. Further, Zhou et al. (2022) corroborated that urban social infrastructure, along with energy and water resources, align with city-scale effects, resonating with the United Nations Sustainable Development Goals. Such patterns, in line with urban scaling theory, are typically reflective of deliberate human planning, design, and governance. The practical application of scaling theory in social production, particularly in macro-level cost management and goal setting, demonstrates robust nonlinear simulation and predictive capabilities. Consequently, it is instrumental in devising strategic management practices and solutions to bolster productivity.

Previous research has predominantly concentrated on the scaling laws of economic and social systems (Batty,

Table 1 Scaling coefficients of urban system elements

Elements	Indicator	Scaling coefficient lower limit	95%CI	Data source
Invention	New patents	1.27	± 0.02	Bettencourt et al. (2007)
Invention	Inventors	1.25–1.47	± 0.03/± 0.06	Bettencourt et al. (2007); Gomez-Lievano et al. (2017)
Invention	Supercreative employment	1.15	± 0.04	Bettencourt et al. (2007)
Productivity	GDP	1.13–1.26	± 0.10/± 0.017	Bettencourt et al. (2007)
Productivity	Wholesale brokers	1.29	± 0.03	Gomez-Lievano et al. (2017)
Productivity	Total wages	1.12	± 0.03	Bettencourt et al. (2007)
Productivity	Bank deposits	1.08	± 0.05	Bettencourt et al. (2007)
Productivity	Total employment	1.01	± 0.02	Bettencourt et al. (2007)
Consumption	Total housing	1.00	± 0.01	Bettencourt et al. (2007)
Consumption	Electrical consumption	1.00	± 0.17	Bettencourt et al. (2007)
Consumption	Household water consumption	1.01	± 0.10	Bettencourt et al. (2007)
Education	High school	1.00	± 0.00	Gomez-Lievano et al. (2017)
Education	Collage	1.11	± 0.02	Gomez-Lievano et al. (2017)
Health	New AIDS cases	1.23	± 0.05	Bettencourt et al. (2007)
Health	Chlamydia	1.06	± 0.02	Gomez-Lievano et al. (2017)
Health	Syphilis	1.46	± 0.05	Gomez-Lievano et al. (2017)
Health	All-cause of mortality	0.89–1.13	± 0.05	Bilal et al. (2021)
Social security	Serious crimes	1.16	± 0.05	Bettencourt et al. (2007)
Social security	Robbery	1.35	± 0.03	Gomez-Lievano et al. (2017)
Social security	Burglary	1.01	± 0.02	Gomez-Lievano et al. (2017)
Infrastructure	Gasoline stations	0.77	± 0.03	Bettencourt et al. (2007)
Infrastructure	Gasoline sales	0.79	± 0.06	Bettencourt et al. (2007)
Infrastructure	Length of electrical cables	0.87	± 0.06	Bettencourt et al. (2007)
Infrastructure	Road surface	0.83	± 0.08	Bettencourt et al. (2007)
Pollution	Waste water	1.15	± 0.04	Lu et al. (2024)
Pollution	Municipal solid waste	1.04	± 0.05	Lu et al. (2024)
Pollution	GHG emissions	0.85	± 0.10	Lu et al. (2024)

Notes: GDP, Gross Domestic Product. AIDS, acquired immune deficiency syndrome. GHG, greenhouse gas.

2008; Bettencourt, 2013; Zünd and Bettencourt, 2019; Lobo et al., 2020; Ortman et al., 2020; Lei et al., 2022), with scant consideration given to the scaling attributes of urban ecological infrastructure, only a few research focusing on scaling factors of park area (Liu et al., 2022) in Chinese cities. Ecological infrastructure, as well as ecological space, mentioned in this paper focus on the ecosystem part of the Chinese Nature-based Solution in urban systems and includes more than only vegetation patches or single man-made infrastructure, which tries to establish a framework that incorporates the relevant components of the urban ecosystem. In China, Nature-based Solution (NbS) is a wide-ranging concept that contains native ecosystem areas, artificial infrastructure, and even the win-win strategy of environmentally friendly and human wellbeing benefits, such as renewable energy development, sustainable agriculture, and forest management (Shah et al., 2023; Zhu et al., 2024). Ecological infrastructure plays a crucial role in fostering urban resilience and enhancing the living quality of cities by delivering essential ecosystem services such as food provision, water resources, air purification, and climate regulation as an integral component of urban planning. A comprehensive understanding of the scaling laws governing urban ecological infrastructure is imperative for informing future planning and forecasting developmental trends. Current researchers have differing perspectives on urban ecological infrastructure, which leads to the fact that theory and methodology are not unified on the understanding, definition, and quantification (Gong et al., 2020; Xu et al., 2021; Kowarik, 2023). For instance, the debate persists on whether to include only man-made ecological infrastructure or also natural ecological spaces and how to account for the varying degrees of human intervention in urban green spaces (Yuan et al., 2023). A common practice in academic research is to classify all green areas inside urban boundries as ecological infrastructure, ignoring the variety of functions that these places may have, including arable lands designated for food production. Moreover, the peripheral natural spaces of cities, though less affected by human activities, fall within urban jurisdiction and thus require consideration. Additionally, some studies have overlooked the intrinsic value and benefits of ecological infrastructure, focusing solely on spatial metrics like area (Tzoulas et al., 2007; Wolch et al., 2014). Research on sustainable urban morphology has also neglected natural urban elements, including greenery, water features, and biodiversity, which are critical to ecosystem health (Zhang et al., 2023). Therefore, a pressing need comes up for further investigation into whether urban ecological infrastructure demonstrates scaling characteristics analogous to those observed in quantity and quality, which provide valuable theoretical insights for the planning and development of urban ecological systems.

2 Urbanization and urban ecology

The exploration and validation of urban ecological laws have received insufficient attention. Existing studies on the correlation between urbanization and urban ecology predominantly focus on spatiotemporal heterogeneity within ecological elements. Researchers analyze the dynamics of urban ecological components, particularly vegetation coverage, spatial distribution patterns, and temporal trends in urban green spaces. Common methods for studying spatiotemporal changes in vegetation coverage include statistical analysis, field research, and remote sensing vegetation index models. For instance, Piao et al. (2019) compared vegetation index time series from various remote sensing satellite sensors, revealing a fluctuating global trend of increased greenness over the past four decades. However, variations exist across regions and seasons, with 34% of the vegetated areas experiencing an increase in greenness and only 5% experiencing a loss of vegetation greening, but with large differences in various regions and seasons (Piao et al., 2019). To measure the benefits and costs of urban trees, Soares et al. (2011) conducted a random sample of urban trees in Lisbon, Portugal. Some scholars conducted a literature review of published data and articles on urban trees in different climate zones, including methods and benefits (Roy et al., 2012). When accounting ecosystem elements at the global scale, researchers must consider differences shaped by climate zones, geomorphology, and vegetation phenology. Regarding urban ecosystem functions and services, most values increase as cities expand outward from their centers. However, ecosystem services (e.g., carbon storage, nitrogen sequestration, $PM_{2.5}$ retention, and habitat quality) become unpredictable with increasing city radius (Peng et al., 2017; Sun et al., 2023).

Assessment models for urban ecosystem functions and services encompass various methodologies, including direct measurement methods, willingness survey, remote sensing inversions, scenario simulations, and mechanism models. Direct measurement methods, e.g., equivalence factor methods, convert ecosystem functions and services to a magnitude of value in a uniform economic unit (Wang et al., 2017; Xie et al., 2017). The willingness survey invests willingness to pay for ecosystem services (Loomis et al., 2000). The remote sensing inversion models specifically consist of spatial information on various indicators, such as gross primary productivity, net primary productivity, normalized difference vegetation index, biomass, and evapotranspiration directly/indirectly obtained and measured via sensors at large scales to represent the actual magnitude of the value of each element on the earth’s surface (Piao et al., 2018; Lee and Brown, 2021; Liu et al., 2023b). One example of scenario simulation and prediction models is the InVEST model, which allows to measure magnitudes of the value of multiple ecosystem services in closed study areas under set scenarios, as well as trade-off/synergistic relationships between services (Nelson et al., 2009). Mechanism models include emergy analysis (Brown and Ulgiati, 2004; Chen et al., 2023), ecological network models (Chen and Chen, 2015; Fath et al., 2019), life cycle assessment models (Koellner et al., 2013), etc. Through the visualization of ecological processes such as energy fluxes and nutrient cycles, mechanism models make it possible to track the interactions between mechanistic processes.

Additionally, an in-depth study of the interactions between urbanization and the ecological environment constitutes a branch of research on urban system complexity. Urban infrastructure (including buildings, transportation, and energy transmission) and ecosystems (including blue-green infrastructure) are crucial subjects in the study of urbanization. By mapping these interrelationships using coupling relationships, interactions between the studied objects are made visible (Sharifi and Yamagata, 2016). Previous studies have explored thresholds, feedback loops, time lags, resilience, heterogeneity, and nonlinear dynamics within human and natural systems (Liu et al., 2007; Shao et al., 2024). These mechanisms embody the complex characteristics of interactions between urbanization and the ecological environment during the evolution of urban ecosystems. Notably, Sun et al. (2023) identified a critical threshold between ecosystem service value and urban radius, observing an evolution from linear to S-shaped relationships and exponential growth or decay as the urban agglomeration center expands outward.

Alterations in the patterns of urban green spaces directly impact the processes and functions of urban ecosystems, which, in turn, affect the benefits derived from ecosystem services. Urban ecosystems furnish open spaces for recreation, contribute to a cleaner environment that reduces disease, regulate temperature and humidity to counteract the urban heat island effect, serve as essential carbon sinks, and offer various services such as soil sequestration and nutrient retention. Spatiotemporal shifts in green spaces can lead to direct or indirect modifications in ecological processes and functions. A marked reduction in urban ecological infrastructure can precipitate a significant deterioration in the quality of critical ecosystem services, including constraints on green open space resources, increased air pollution and water quality degradation (heightening the risk of diseases), intensified urban heat island effects, nutrient loss in soil, land desertification, and other adverse outcomes (Liu et al., 2023a; Niu et al., 2023; Zheng et al., 2023).

To date, scant research has elucidated the intricate laws governing ecosystem development and evolution within urban contexts. This is partly because urban ecosystems possess numerous attributes and characteristics that are challenging to quantify, rendering individual indicators insufficient to encapsulate the entire system. In urban studies models and empirical research (Johnson and Munshi-South, 2017; Govaert et al., 2019), human economic and social activities—key drivers of urbanization—are often distilled into a limited set of aggregated variables, such as impervious surface area and population density. However, these variables alone frequently fail to capture the full complexity of urban systems' developmental changes (Szulkin et al., 2020). Moreover, ecological and evolutionary responses within cities are commonly treated as constants, overlooking the dynamic shifts and interactions with urbanization processes (Johnson and Munshi-South, 2017; Govaert et al., 2019).

Various quantification methods are available for assessing urban ecosystems across different ecological aspects. When evaluating species diversity within ecosystems, metrics such as species richness, evenness, and diversity indexes (e.g., the Shannon–Wiener index) provide insights into ecosystem health and the complexity of biological communities. Ecological footprint analysis gauges the impact of human activities on ecosystems by calculating the biologically productive areas necessary to sustain specific lifestyles or economic practices (Wackernagel and Rees, 1996). Scholars have also employed landscape ecology tools, including landscape indexes (e.g., patch density, edge density, and landscape connectivity), to quantify the spatial structure and patterns of landscapes (McGarigal, 1995). Urban ecosystem evolution adheres to consistent laws, regardless of specific research contexts. However, studies that combine urbanization and ecology often remain siloed, leading to contradictory findings and hindering uniform conclusions. Emergy analysis not only reflects changes in green space quality resulting from alterations in the number of urban green spaces but also simplifies subsystem energy flows, bypassing complex metabolic reactions. To advance urban sustainability and resilience, a systematic exploration of urban metabolism is essential particularly from an emergy perspective (Cristiano et al., 2020). In emergy theory, an urban system is a collection of distinct materials generated as a result of the transformation of different energy sources. Complex energy transformation and metabolic processes occur in many aspects of human society, including production and ecosystems. Energy comes in a variety of forms and qualities (Brown and Ulgiati, 2004), including material flow as containers and energy flows as direct carriers. From emergy theory to methodology, the geobiosphere emergy baseline (GEB) is established and refined in order to measure the emergy of how processes and interactions occur in ecosystem through energy transformation and heat dissipation (Brown et al., 2016; Brown and Ulgiati, 2016).

3 New insights into scaling theory from the thermodynamic perspective

3.1 Scaling theory of ecosystem energy metabolism from the thermodynamic perspective

Ecological thermodynamics, a specialized field within thermodynamics, examines the energy conversion processes and nutrient cycles within ecosystems. It employs the principles of thermodynamics to delineate and scrutinize the functional processes of organisms, populations, communities, and entire ecosystems. This includes the input, storage, dissipation, and output of energy, along with the associated matter flows. Ecological thermodynamics focuses on the efficiency, productivity, stability, and sustainability of ecosystems, particularly in relation to environmental shifts and biological activities. Through a thermodynamic lens, one can quantify the functional state of ecosystems, evaluate their reactions to external disturbances, and forecast the potential impacts of enduring environmental changes on ecosystems (Odum, 1971; Patten et al., 1976; Ulanowicz, 2012). In this context, the connectivity of nodes and the infrastructure of networks within ecosystems are facilitated by structures and matter-energy flows. The inherent scale-free nature of ecological networks dictates that they adhere to scaling laws, meaning that within these networks, a select few nodes serve as highly connected hubs, while the majority possess fewer connections. Recent studies have identified scaling law attributes in the matter-energy relationships of ecological networks at the ecosystem level (Galiana et al., 2022). Consequently, it is a logical deduction that ecosystems, viewed through the prism of ecological thermodynamics, exhibit a pronounced adherence to scaling theory.

Marquet et al. (2005) summarized the relationship between power law and the scaling relationship of ecosystems through a series of evidences. The power law in an ecosystem represents the constant mathematical relationship between two ecological attributes ($Y = \alpha x^{\beta}$), that is, no matter what changes in the shape of the elements in the ecosystem, the proportional relationship remains unchanged. Power law emphasizes this bivariate relationship, which can be many combinations of two elements. The scaling relationship is the proportional relationship between size and energy transformation at all levels of the ecosystem (Marquet et al., 2005), emphasizing the combination of body size and metabolism. Therefore, to unify the definition in this study, ecosystem scaling law focuses on the power-law constant mathematical relationship ($Y = \alpha x^{\beta}$) between the size of the ecosystem elements at all levels and the energy flow in urban ecosystems, and the constant power-law relationship derived from the relationship between the size of the urban ecosystem and the energy metabolism process. The power law of the ecosystem mentioned in many studies and the scaling theory of urban economy and society can be included in the research scope of the scaling law of the urban ecosystem.

At the species level, ecosystems exhibit classical allometric scaling. Recent studies have also uncovered that cross-level energy transfers exhibit quantitative and qualitative power law correlations and that the complexity of ecological networks is characterized by significant power law distributions. Consistent with the principle of ecosystem stability, there is a negative linear relationship between population density and individual organism size, with energy consumption diminishing at varying rates across different ecosystem levels and organism sizes (Makarieva et al., 2004). The right of organisms to occupy ecosystem space and access resources correlates directly with body weight, with human ecological space being relatively smaller than that of other mammals of equivalent weight (Makarieva et al., 2011). Additionally, intergenerational information flow, social interactions, and class role relations influence human population growth, constrained by the ecological limits of energy flow and resource availability, leading to human population dynamics that diverge from those of other organisms.

Studies on cross-level energy flow provide evidence that biospheric hierarchical systems adhere to scaling law distributions. Liu et al. (2021) analyzed emergy accounting data from 2001 to 2014 for over a thousand products and 213 countries, revealing that these systems often trade efficiency for increased energy output during evolution, exhibiting a high degree of self-organization and an inverse linear scaling law distribution. These systems follow uniform laws, including order-of-magnitude boundaries with maximum limits for resource quantity and quality, typically at an order of magnitude of 24 (10^{24}), and an energy conversion efficiency of approximately 14%, or a 7:1 input-to-output ratio. This research encapsulates the inverse scale invariance observed in the evolution of various biospheric hierarchical systems, highlighting their complexity and multi-scale nature across temporal, national, and regional dimensions. Urban ecosystems also demonstrate considerable complexity in their attributes, composition, and interactions, with scale invariance mirrored in organismal metabolism (White et al., 2022).

In ecosystem networks, species richness and the complexity and area of biological relationship networks also exhibit scaling law characteristics. As the distribution area of species at various levels expands, the complexity of these networks increases. This complexity includes factors such as the number of species, interspecific relational connections, and species combinations. These relationships follow a power law function across all spatial scales and interactions. Interestingly, power law variability is more pronounced at biogeographic scales compared to regional scales. This suggests that network complexity becomes less predictable as we move to larger spatial contexts. However, despite these variations, the vertical diversity of ecosystems—specifically, the proportion of species at different trophic levels—remains essentially stable. This stability is attributed to the self-adaptive and self-organizing abilities of ecosystems (Galiana et al., 2022).

3.2 Exploration of urban energy metabolism laws from the ecological thermodynamic perspective

From the ecological thermodynamic perspective, the influence of urban development and internal operations on resource and energy transmission, consumption, and waste mirrors the metabolic processes observed during ecosystem evolution. This analogy is accompanied by an increase in entropy and energy efficiency. In the context of urban metabolism, we view the urban unit as a "superorganism" (Odum, 1971; Patten and Odum, 1981). Based on this thermodynamic viewpoint, urban organisms function as entities within ecosystems, modeling the flow of nutrients and energy through resources (Conan, 2000). These processes reflect the complex responses involved in the growth of urban organisms and the cascade effects that occur across various energy levels (Ramaswami et al., 2018; Qu et al., 2023).

Numerous studies have explored scaling laws at the species and population levels. By integrating scaling law phenomena (Table 2) potentially arising in the urban economic-social-ecological composite system, we observe that scaling laws—ranging from inverse to sub-linear to linear—generally manifest at individual and species levels. However, super-linear scaling laws characterize the entire system. Notably, empirical evidence for super-linear scaling laws is lacking at broader organism levels due to limitations in energy supply and metabolism during growth and reproduction (West and Brown, 2005). Whether at the individual organism or system level, energy efficiency increases as the scale of the organism or system expands (Pulido Barrera et al., 2018). As complex urban systems evolve from micro to macro levels across spatial scales (encompassing individual humans, productive and residential units, communities, cities, regional-national clusters, and internationalized complexes), a transition occurs in scaling laws—from sub-linear to linear to super-linear. This shift suggests that inter-individual cooperation enhances differentiation and overall efficiency (Liu et al., 2021). Thus, from a thermodynamic perspective, energy supply and consumption processes in urban composite systems can be deconstructed from system-level linear/super-linear scaling laws to individual-level sub-linear scaling laws, ultimately validating scaling laws at the overall urban system level.

Energy transformation and dissipation are pivotal thermodynamic mechanisms that propel the evolutionary processes of ecosystems. Schneider and Kay (1994) theorized that ecosystems undergo dynamic evolution in accordance with the second law of thermodynamics, which involves establishing energy gradients through dissipation and the internalization of energy. The self-organized energy transmission behaviors within these systems serve as adaptive strategies for survival and evolution. Ecosystems that thrive are those adepts at maximizing the use of energy inputs to fulfill the

Table 2 Summary of scaling types in urban complex systems

Type	Scaling coefficient	Driving factor	Cases	References
Inverse scaling	$\beta < 0$	Optimize and improve efficiency	The ecological scale relationship between average population density (Y) and average species size (X) showed an inverse scale relationship ($\beta < 0$), such as primary consumers of mammals ($\beta = -0.75$) and Amazonian bird communities ($\beta = -0.22$). Changes in the equilibrium number or carrying capacity of an individual organism are inversely proportional to body size.	Damuth (1981); Brown et al. (2004)
Sub-linear scaling	$0 < \beta < 1$	Optimize and improve efficiency	There is a classical sub-linear scale relationship between an organism's metabolic rate (Y) and its body weight (X) ($0 < \beta < 1$), for instance, Kleber's law ($\beta = 3/4$). The relationship between total biomass and body size was also sub-linear.	Kleiber (1947); West & Brown (2005); Brown et al. (2004)
Linear scaling	$\beta = 1$	Living and consumption	An individual-based human development indicator (Y) is usually linearly related to city size (X) ($\beta = 1$), such as total housing stock in the United States ($\beta = 1.00$), household electricity consumption in Germany ($\beta = 1.00$), and household water consumption in China ($\beta = 1.01$).	Bettencourt et al. (2007)
Super-linear scaling	$\beta > 1$	Information innovation, wealth generation, resource development	The total output benefit (Y) (e.g., wages, income, GDP growth, bank deposits, new patents) and city size (X) show a super-linear scale relationship ($\beta > 1$). The scaling coefficient of new patents in the United States is $\beta = 1.27$, R&D employment in China is $\beta = 1.26$, and GDP in the European Union is $\beta = 1.26$.	Bettencourt et al. (2007)

Notes: The content was from (Pulido Barrera et al., 2018).

survival requirements of both organisms and their environments. The “scaling law” characteristics observed in ecosystems arise from their evolutionary trajectory toward greater energy use efficiency. This trajectory is governed by hierarchical thermodynamic and systemic constraints, leading to a progressive evolution of the biosphere’s energy gradients. Globally, ecosystems predominantly display inverse and sub-linear scaling laws, with linear scaling laws being less common. This pattern occurs because systems adhering to linear and super-linear scaling laws often achieve more efficient energy conversion and degradation, albeit at the cost of other systems and stored resources, such as fossil fuels. Nevertheless, as ecosystems evolve, they aim to maximize the benefits of energy transformation while sustainably increasing total dissipation and developing more complex structures and diversity levels. This evolution prioritizes maximizing energy transformation benefits without exhausting the energy needs of other systems, opting for economies of scale in energy transfer. Consequently, this leads to the emergence of more mature ecosystems.

Although the energy metabolism of urban systems and ecosystems varies significantly in form, they share a fundamental thermodynamic mechanism. In both, energy inputs undergo transformation, degradation, and dissipation, creating gradients of energy. Cities, as advanced conglomerations for human activity, represent a stage of societal development beyond that of early ecosystems. This advancement is reflected in the higher energy levels of urban systems, which draw upon ecological capital—resources originally produced by ecosystems through energy transformations (Odum, 1971; Pickett et al., 2001; Costanza et al., 2014). As urban areas expand, they dissipate energy increasingly as heat, depleting energy sources and accelerating entropy production (Bristow and Kennedy, 2015). Similar to natural ecosystems, urban socio-economic systems establish energy gradients through these transformations and dissipations. Disparities in energy distribution prompt the system to initiate complex responses to overcome these gradients. There is a global correlation between urban expansion and total energy consumption. The energy scaling law suggests that the combined energy dissipation of a large city and several smaller ones exceeds that of multiple medium-sized cities with an equivalent total population (Bristow and Kennedy, 2015). Moreover, urban growth is not merely a sum of individual contributions but also includes the compounded value from cooperative interactions. This synergy results in certain urban metrics, such as residents’ income, patent creation, and crime rates, displaying super-linear scaling at the city level (Bettencourt, 2013).

3.3 Should ecological elements in urban systems conform to scaling laws from the thermodynamic perspective?

The essence of the scaling law is that each element in a system increases, stabilizes, or decreases proportionally with the expansion of the size such as area, volume, and number of populations (Marquet et al., 2005; Bettencourt et al., 2007). In Odum’s emergy theory, the components of ecosystems are the products of the conversion of solar energy, geothermal energy, and tidal energy under different processes and are the higher-quality products generated by different renewable input energy at the conversion rate. System subunits at different hierarchical scales can be connected at the upper and lower levels through conversion rates of available energy (exergy), so that the crossing from the first level to the third level, the intergenerational relationship, can also be indirectly represented as a scaling-law relationship. The transformation efficiency is jointly determined by the two transformation efficiencies from the first level to the second level and the second level to the third level. Changes in the first level will be communicated to the second and third levels through changes in the proportionality relationship. Although there is a difference in the conversion efficiency, this is only a numerical difference; essentially the energy conversion efficiencies of the different system levels are in a constant interval. The conversion efficiencies remain relatively constant from the subunit of the system at the previous scale to that at the next scale in Liu et al.’s research (2021). Differences in transformation factors lead to the complexity of the system. The existence of multiple features within a complex system (e.g., optimization strategies) causes the power law distribution of subsystems to manifest as fluctuations within the interval.

The same is true of the ecological components located in urban systems, which generate secondary energy from primary energy at a certain conversion rate, undergo multiple energy transformations through various ecosystem functions and processes, and finally form a specific ecosystem. The urban system is formed by the transformation of primary energy resources through higher quality and long-term evolution. And its primary energy input is much higher, so that it requires input from many other areas. Compared with the ecosystem, the economic and social system inside the city has a higher level of energy quality due to its more transformation times and more complex transformation process, while the quality level of the ecological component is relatively low, which belongs to the residual emergy of the natural ecosystem and reconstructed emergy from human investment. In the process of urbanization, the formation of economic and social systems and ecosystems is inevitably accompanied by heat dissipation. Among the subunits of the system at the same hierarchical scale, urban systems undergo similar transformation processes, so that the elements of urban systems at various city sizes show consistent scaling law characteristics.

Urban ecosystems are influenced by both internal and external factors to adhere to scaling laws to varying degrees. Internally, the metabolism of living organisms is driven by the flow of thermodynamic energy, which catalyzes a sequence of developmental and evolutionary processes within ecosystems. Throughout these processes, the self-adaptive and self-organizing capabilities of the system permeate different ecological levels, fostering interactions both within and across these levels, thus contributing to the establishment of consistent ecosystem laws.

In ecosystem, population dynamics, community structures, and ecosystem functions—which include things like service value, nutrient cycles, decomposition, and primary productivity—are all impacted by changes in genetic diversity and habitats (Alberti et al., 2020). Evolution at lower levels can instigate system-level evolution, prompting a shift from one state to another (Cumming and Peterson, 2017). During this transition, the system engages in continuous feedback loops and selective processes that favor its self-perpetuation (Lenton et al., 2021).

On the basis of maintaining the original ecosystem functions and processes, urban ecological infrastructure also provides ecosystem services for human beings. In terms of water management, sponge cities provide natural solutions for optimization strategy of water resource for urban population (Benedict and McMahon, 2012; ElZein et al., 2016; Li et al., 2022; Shah et al., 2023). In terms of thermal risk, urban ecosystems play a crucial role in mitigating the urban heat island effect and reducing heat exposure risks for populations through cooling and humidification via evapotranspiration (Cui et al., 2021; Li et al., 2023; Song et al., 2024). The relationship between the city and the original ecosystem has gradually shifted from the unilateral spatial erosion and resource exploitation of the city to the mosaic of built-up areas and ecological spaces, fostering a new ecological urban morphology (Benedict and McMahon, 2012).

Beside human interventions across various dynamic mechanisms (Gao and Li, 2011; Ouyang et al., 2021), the external impacts of urbanization on the urban ecological infrastructure are multifaceted, driven by the geomorphology types at different altitudes, land-sea thermal difference, and the seasonal movements of monsoon zones are all the causes of the spatial heterogeneity of heat and water in terrestrial ecosystems and their combined effects, which have an indirect impact on the development of ecological landscapes and the provision of ecosystem services (Yu et al., 2013).

The connectivity of urban ecological infrastructure is related to the formation of urban infrastructure networks and may keep forming scale-free characteristics due to positive synergies of ecological connectivity and urban renewal (Egerer et al., 2020; Felipe-Lucia et al., 2020). Only a few ecological infrastructures have most adjacent infrastructures, and most ecological infrastructures have a small and balanced number of adjacencies.

Influenced by policy directions and human health imperatives, urban ecological spaces have been shaped through deliberate interventions, including the infusion of economic capital and the transformation of ecological capital within urban design and construction. Different transportation planning measures may result in different ecological spatial exposures of urban populations, with specific policies resulting in co-benefits for humans and ecosystems. For example, increasing public transportation, reducing automobile use and increasing ecological infrastructure will not only reduce carbon emissions and environmental pollution, such as air pollution and noise, but also enhance physical activity, mental health and social integration (Nieuwenhuijsen, 2016; Yang et al., 2024). Additionally, urban ecological spaces provide social spaces and venues for migrant populations, promote social integration of migrant populations, and enhance human environmental perception and emotional dependence at the psychological level (Dasgupta et al., 2022). Multiple scaling laws in urban scale theory are grounded in demographic interactions; therefore, from a theoretical standpoint, urban ecological infrastructures may adhere to scaling laws to some extent. However, research into the complexity and multi-scale dynamics of urban ecosystems is relatively sparse, leaving a gap in our understanding of the overarching patterns and principles governing their development and evolution.

4 Proposition of scaling law hypotheses on ecological elements in urban systems

Drawing from the literature, we posit that urban ecological infrastructure—artificially constructed, repaired, maintained, and conserved for green and sustainable development—provides essential services such as green spaces and recreational areas to urban populations. This infrastructure is expected to exhibit scaling law characteristics akin to those of other engineered facilities. Its thermodynamic mechanism orchestrates energy gradients through self-organized energy transformation and dissipation, leading to the formation of multistable structures characterized by complexity and multifunctional differentiation. In isolation, without external disturbances, the system's multistable state persists until the energy is fully expended. When external disturbances occur, the system's resilience is evident if it can self-organize and revert to its original stable state, provided the disturbances remain below a critical threshold. However, if the disturbances are too severe, surpassing this threshold, the system may regress to a lower homeostatic level or collapse entirely. Consequently, our hypotheses for urban ecosystem scaling laws encompass the coexistence of multiple stable states due to urban natural resource endowments and the ecological trade-off and threshold effect under socioeconomic pressures.

4.1 Multistable coexistence and scaling law in urban metabolism

The dynamics of urban ecosystems exhibit multistability, characterized by transitions between system states. These transitions occur within the multistable structures of urban ecosystems until the system's resilience to external disturbances and the critical collapse point are discerned. Hence, the scaling laws governing urban ecosystems also involve multistable coexistence at finer scales.

In urban ecosystems, spatial disparities in natural resource distribution lead to uneven regional ecological spaces, where multiple states coexist and compete within reasonable bounds alongside human activities. A similar phenomenon occurs in grassland ecosystems. Consider the zoning of African grasslands: varying precipitation levels give rise to multistable structures, ranging from expansive grasslands with abundant water resources to meadow patches in drylands and further to desert zones with scarce precipitation (Rietkerk et al., 2021). The number of spatial dislocations (N) of banded vegetation in arid landscapes strictly follows the topological law N–$\log(x/B)/x$, which is related to the direction of water flow (x) (Pinto-Ramos et al., 2023).

Zooming in from a global perspective to local river basins, we find analogous multistable coexistence due to spatial heterogeneity in natural resource allocation, influenced by differences in energy metabolism. Scaling law variations across ecosystem states, driven by external disturbances, yield pronounced early warning signals of system collapse. Experimental studies reveal that plant patch size and frequency respond differently to low, medium, and high environmental stresses (e.g., drought and grazing intensity), resulting in distinct scaling law distributions. Early warnings emerge when scaling laws shift from linear to downward-curved, limiting maximum patch size and patch numbers as vegetation coverage transitions from high to low (Fig. 1). When environmental pressures exceed vegetation tolerance, vegetation patches vanish, giving way to deserts (Schneider and Kéfi, 2016; van den Elsen et al., 2020).

In realistic scenarios, ecosystems face multiple external disturbances (e.g., drought and grazing) with relatively high environmental intensity (Li et al., 2023). Consequently, certain sets of states within the ecosystem's spatial patch multistability exhibit scaling law characteristics. The coexistence of multiple states within local bottom-up areas constitutes a continuously stable state for the overall energy metabolism of the system.

Under multiple eco-spatial conditions of transition from high ecological resource endowments to low ecological resource endowments, population density, activity intensity, and activity content within cities will vary. Thus, ecosystems may exist in multiple continuously and dynamically changing states of distribution with human survival activity ranges set. People may either conserve areas with high ecological resource endowments as primordial ecosystems or exploit them, thereby hastening the degradation of ecological spaces, which leads to some problems, such as declining vegetation coverage, encroachment of ecological spaces, and decline in ecological quality. However, under the guidance of reasonable policies on ecological infrastructure, the vegetation coverage of cities has been substantially increased when they are expanding outwards. Within individual cities, new urban areas expand ecological infrastructure and pay attention to ecological quality, while old urban areas face the pressure of decreasing green spaces. Small-scale cities are still in the early stage of ecological infrastructure development (Feng et al., 2024). The protection and construction of urban ecological infrastructures interact with the mosaic distribution and energy metabolism of economic and social infrastructures. Multiple complex interactions promote the formation of multistable coexistence of urban socioeconomic systems and urban ecosystems, thus reflecting scaling law characteristics in different dimensions such as quantity, quality, and structure.

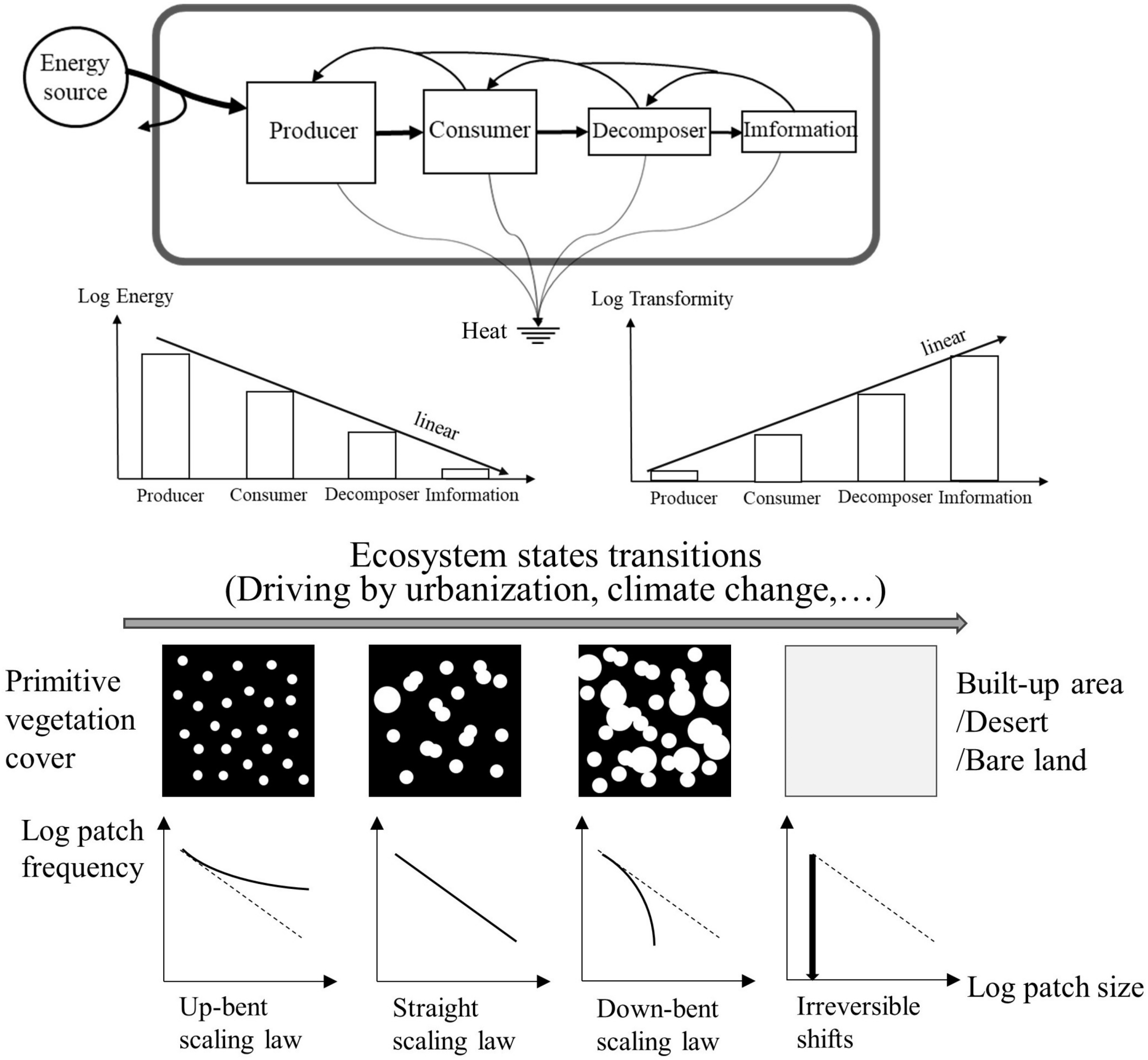

Fig. 1 The diagram of energy hierarchy and multi-level transformation of urban ecosystem conform to the scaling law.

4.2 Ecological trade-off and threshold effect hypothesis under socioeconomic perturbations

Urban ecosystems frequently encounter disturbances from various economic and social factors. When the ecological niches of economic and social systems intersect with those of natural ecosystems, a competition for space and energy ensues among the subsystems. Influenced by ever-changing drivers, elements within the ecosystem undergo spatial natural selection and adjust their energy metabolism through self-organization, leading to the emergence of new, optimal ecological niches within the complex urban framework. The evolution of urban ecosystems encompasses the orderly transition and transformation of these niches, resulting in trade-offs such as spatial and energy competition. In urban agglomeration, comprising core and peripheral cities, each city carves out its unique functional ecological niche (Xu et al., 2018). Within a single city, various system elements engage in mutual competition, cooperation, and coexistence, influencing the population, resources, environment, economy, and society either positively or negatively (Wang et al., 2016). The trade-off relationships between ecosystem services within urban ecosystems are markedly scale-dependent, adapting to climate changes and regional environmental features, with trade-off intensity and content varying across scales (Rodríguez et al., 2006). In the multi-factorial trade-offs of intricate urban systems, outcomes at the systemic level impact the trade-offs and synergistic interactions among the system's components.

The trade-off between ecosystems and economic and social systems reflects the adaptability and resilience of urban ecosystems. Cumming et al. (2006) and Cumming (2013) highlight how the varied distribution and growth processes across city sizes can lead to scale mismatches, which are disruptions and inefficiencies in socio-ecological systems that occur when the scale of environmental changes aligns with the scale of managing social organizations. Such mismatches can reduce socio-ecological resilience, increase the risk of mismanaging natural resources, and potentially degrade human well-being. Research into urban economic system vulnerability, such as that by Shutters et al. (2015), reveals that cities with greater resilience fare better during economic downturns, whereas less resilient cities may perform better economically in stable times. Urban green spaces, often pressured by housing and commercial development demands, nonetheless provide significant economic benefits to local communities and exhibit a diminishing marginal value with distance (Perino et al., 2014). Ecological trade-offs extend beyond simple service exchanges; they involve complex nonlinear responses to human activity (He et al., 2024). The triangular relationship between nighttime light intensity and the normalized difference vegetation index illustrates the trade-offs and thresholds between economic, social, and ecological systems, with multiple stable states coexisting within these spatial parameters (Wu et al., 2023). While most urban ecological trade-off studies focus on the relationships between ecosystem services (Rodríguez et al., 2006; Spyra et al., 2020; Cueva et al., 2022), there is a need for more research on the trade-off effects between ecosystems and economic and social systems. Understanding these trade-off relationships and the thresholds of state changes is crucial for developing urban strategies and policies that enhance urban ecological resilience.

5 Conclusions

This study critically reviews the scaling theory of urban socioeconomic systems and the thermodynamic principles governing urban metabolism to propose that certain urban ecosystem components exhibit scaling laws analogous to socio-economic systems. The thermodynamic perspective on urban ecosystems' energy flow and material transformation fosters a cohesive understanding of urban ecological principles. Across various urban hierarchy, the energy flow within ecosystem elements displays a distinct scaling law pattern in terms of energy and transformity. System state shifts result in a transition of ecological elements' scaling laws from an upward curve to a linear progression and then to a downward trajectory, reflecting mass gradient changes due to unbalanced energy flow.

In the context of urbanization-driven ecosystem state transformations, this disequilibrium in energy flow underpins the coexistence and relative stability of diverse ecosystem states across different mass gradients. The prevalence of states with clear scaling laws leads to spatial and efficiency-based trade-off interactions with the socio-economic system.

Future research should incorporate this hypothesis into studies on urban ecosystem evolution and the effects of urbanization, thereby enriching the unified theoretical framework of urban ecosystems. Methodologically, the nonlinear dynamics of urban ecosystem state transformations as dictated by energy flow are described by ecosystem scaling laws. This approach enables the construction of a dynamic model for the urban complex system, providing precise quantification of the intricate evolutionary interactions within the urban ecosystem. The scaling law's scale-free attribute, as opposed to randomness, serves as a theoretical foundation, enhancing the scientific rigor of ecosystem reaction process simulations and predictions and supporting subsequent ecological law research.

Case studies should pay heed to the scaling law and potential scaling mismatches within ecosystems. If an urban ecosystem, typically self-organized according to a unified scaling law, suddenly diverges from this pattern, it may signal an impending state change. The scaling law of urban ecosystems could thus underpin the theoretical basis for identifying ecological security tipping points, offering valuable insights for decision-making and planning in urban ecological infrastructure.

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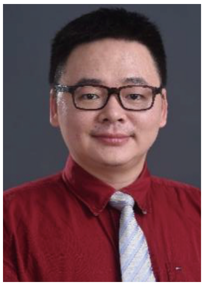
Author Biography



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