https://doi.org/10.15302/J-LAF-1-030053 Received Date | 2023-07-28 Accepted Date | 2024-04-01

Integrating Urban Metabolism With Landscape Disciplines by Applying Technomass

Luis INOSTROZA[1,2,*]

1 Faculty of Regional Development and International Studies, Mendel University in Brno, Brno 613 00, Czech
2 Vicerrectoría de Investigación y Doctorados, Universidad Autonoma de Chile, Santiago 7500912, Chile

*CORRESPONDING AUTHOR
Address: Zemedelska 1, Brno 613 00, Czech
Email: luis.inostroza@mendelu.cz

ABSTRACT

Urban metabolism provides a robust framework for analyzing urban development and its impacts. However, several conceptual and operational shortcomings have constrained the application of urban metabolism in understanding the overall urban processes, limiting the transfer of its potential benefits to design and planning. This article systematically analysed the rationale of the current urban metabolism models, focusing on four prevailing shortcomings from a transdisciplinary perspective: 1) utilizing an isolated state approach, which treats urban systems as isolated from other ecosystems; 2) ignoring internal processes within urban systems, known as the black box paradox; 3) employing a linear material approach that focuses on the path of single materials; and 4) overlooking the material productivity of urban systems, where energy and materials entering the system are used to reproduce the urban material structure and generate goods and tradable products. While these issues have been identified individually in existing scientific literature, there is a lack of holistic solutions. This article proposes an enhanced urban metabolism analytical approach—the ecosystem approach applying "technomass"—to address these shortcomings and provide practical solutions in landscape architecture and planning disciplines for sustainable urban development.

KEYWORDS

Urban Metabolism; Technomass; Urban Ecology; Ecosystem Approach; Metabolic Flux

HIGHLIGHTS

- Points out four prevailing shortcomings of the current urban metabolism models
- Rethinks urban systems as ecosystems composed of biomass and technomass
- Proposes the ecosystem approach to integrate urban metabolism with landscape disciplines

EDITED BY Yuting GAO, Tina TIAN

1 Introduction

The prevailing Western scientific separation between nature and society has profoundly affected urban metabolism (UM) studies. Since Abel Wolman's seminal publication in 1965, UM has been defined as the material and energy exchanges between urban systems and the environment[1]~[3]. This perspective conceives cities as isolated entities, independent of other urban and native ecosystems while not adhering to the laws of thermodynamics. Such a viewpoint restricts the great potential of UM to address crucial issues for promoting sustainable urban development.[1][4][5]

UM has contributed a wealth of studies analysing the materials and energy flows in urban contexts[1][6], using methods such as material flow analysis (MFA) and life cycle analysis (LCA). The analyses of physical flows aim to describe the biophysical relationships between urban areas and their surrounding environment[7][8]. However, such studies often overlook important urban factors, e.g., locations of natural capital extraction, urban forms, and geographical distributions of activities and people. Attributing metabolic fluxes to people, places, land uses, buildings, and infrastructure is the cornerstone to unveil the real UM for sustainable development, which should be based on circularities that also include temporal considerations[9].

Surprisingly, current UM conceptual models disregard the profound material transformations that occur alongside the metabolic processes[5]. Upon examining the UM knowledge, four prevailing shortcomings are identified: 1) utilizing an isolated state approach, which treats urban systems as isolated from other ecosystems[8]; 2) ignoring internal processes within urban systems, known as the black box paradox[2][10]; 3) employing a linear material approach that focuses on the path of single materials[1][2][4][11]; and 4) overlooking the material productivity of urban systems, where energy and materials entering the system are used to reproduce the urban material structure and generate goods and tradable products[7][8].

Overcoming these shortcomings requires using tailor-made indicators, paving the way for transdisciplinary integration and opening relevant avenues for sustainable urban development. This article aims to provide an operational, i.e. ready to be used, alternative for integrating UM studies into landscape architecture and planning.

2 Shortcomings of Current UM Analysis Models

2.1 Shortcoming One: The Isolated State

The concept of UM still relies on the "isolated state," a metaphor known from the works of Johann Heinrich von Thünen, which models the city as a closed system not linked to any other[12][13]. The isolated state of UM fails to recognize the fact that, while cities extract materials and energy from other ecosystems, a profound material transformation occurs, underpinning extensive metabolic exchanges among a broad range of urban and native ecosystems. In reality, cities persistently appropriate matter and energy from other urban and native ecosystems to sustain their metabolism[14][15], which has been a fundamental urban process[16] and driven urban development as a morphogenetic factor since the ancient times[17][18]. For instance, ancient Rome imported copper from Spain, wheat from North Africa, and slaves from various regions. Today, the use of cheap fossil fuels has intensified the planetary extraction and exploitation of natural capital[19].

This perspective extends the urban material structure beyond the physical boundaries of cities and entangles different ecosystems across scales, from regional to global[8], making them fundamental to urban organization and functions. Meanwhile, UM has been locally and globally influential in ecology, economy, and society resulting from the enlarged metabolism. However, UM studies remain narrowly focusing on flows into and out of cities[6][11] by adhering to the isolated state approach, neglecting the role of other ecosystems and the interdependencies and hierarchies among urban systems[7].

2.2 Shortcoming Two: The Black Box Paradox

In science and engineering, a "black box" is understood as a device, a system or an object in terms of its input, output, and transfer characteristics without any knowledge of its internal workings[20]. If not able to investigate the internal processes, people can only guess or hypothesise on what occurs inside, according to what has been done to it (input) and the result of that (output). The current UM models conceptualize urban systems as a black box, only acknowledging and measuring input and output stocks and flows, rather than investigating what happens inside this black box. The functioning of urban system relies on productive circularities, involving the internal processes of production, circulation, transformation, consumption, and accumulation, and the external processes of degradation of materials and energy[21][22], without which forms no UM.

Understanding the relationships between stocks and flows inside the urban black box is fundamental to closed energy and material cycles. However, the underlying relationships between these material stocks, presenting in forms of buildings and infrastructures, and the flows they produce have been little investigated. Indeed, until now, stocks have been estimated regarding remaining flows by using indirect measurements in UM studies[23]. UM can contribute with the necessary knowledge to advance towards circular economy.

2.3 Shortcoming Three: The Linear Material Approach

The linear material approach of UM conceptualizes metabolic fluxes as linear processes, restricting the analysis to individual flows from source to sink[2] and only specific materials crossing the urban boundaries[4][22]. UM has analysed metabolic fluxes using linear material approach based on MFA[24] and LCA methods[25], and most attention has been paid to a myriad of materials, including metals, plastic, and construction materials through standard input and output accountability[11].

However, such a linear material approach neither acknowledge the ecology of the fluxes[4], nor explain the profound material transformations, (metabolic) transfigurations or re-arrangements of components that produce qualitatively new material assemblages[5]. Metabolic fluxes possess both biophysical and economic dimensions, which are necessary to include in UM analysis to advance circular understandings of UM[8]. Understanding the metabolic transfigurations and re-arrangements within, across, and beyond urban systems[5] can clarify crucial aspects of sustainability, covering energy demand, pollution, biodiversity, and human health impacts. Focusing on the complex, non-linear processes of material transformations and assemblages, rather than single elements, provides strong empirical ground for establishing a robust operational platform to assess circular economy claims. From the perspective of landscape disciplines, furthermore, examining material assemblages produced by UM offers a straightforward link to urban forms and landscape planning[26].

2.4 Shortcoming Four: The Production and Reproduction of the Urban Material Structure

Materials and energy entering urban systems are used to reproduce the urban material structure. This reproduction of urban tissue is at the core of UM accumulation process, which requires increasing the global amount of construction materials. UM accumulation processes are fostered by persistent urban expansion. Appropriation of external materials sustains productive circularities, where the material structure of cities is produced and reproduced autopoietically[7][27].

UM strongly depends on material accumulation processes, which reflects all materials that remain materialized as urban tissue in the form of buildings, infrastructure, machines, etc.[22]. The global consumption of construction materials has increased exponentially since the mid-20th century, making the materials of cities increasingly intensive[28]. This trend is the outcome of the persisting urban expansion worldwide[29], implying an accumulation process where the material body of cities grow permanently. This makes the analysis of accumulation a cornerstone of UM studies, but one that is still not fully considered. From a purely phenomenological point of view, material accumulation in urban systems assumes the form of idiosyncratic material assemblages that have been characterized as buildings, infrastructure, etc., which have been largely analysed elsewhere as urban forms[30]. This conceptual relationship between urban expansion and material accumulation opens the door for analysing metabolic influxes and outfluxes which are substantially influenced by particular urban form factors.

3 A Way Forward for UM Studies

UM functions over a planetary circularity of matter, energy, and information, rather than the normally known linear input–output flows[8]. Thus limiting UM analysis within individual urban areas is inadequate. In UM analysis, it is also important to include the characteristics of material structures accumulated in urban tissues[8]. UM not only materializes cities, but also produces profound economic and socio-ecological consequences both within urban systems and in distant urban and native ecosystems[19].

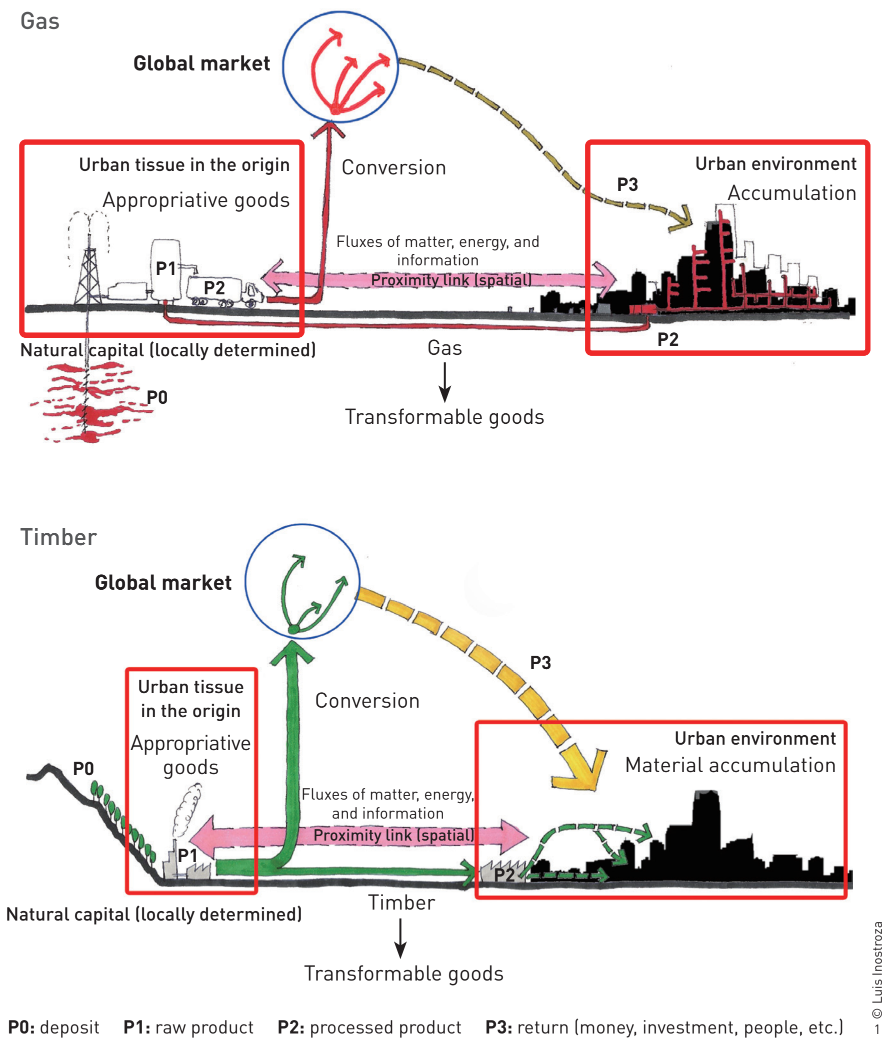
3.1 What Lies Beyond the Isolated State?

Landscape disciplines can help UM plot the complex relationships and ascertain the dependencies between ecosystems over space and time (e.g., the history and ecology of UM). Metabolism and circulation are foundational concepts for analysing the dialectical production of material assemblages and metabolic entanglements, opening a pathway for integrating UM studies with landscape disciplines[5]. The direct and indirect outputs of UM extend far beyond urban cores and affect other urban and native ecosystems[19]. Ecological displacement and uneven ecological exchange have been ascertained in cross-national studies following world-systems theory①[31], suggesting that environmental improvement can cause degradation to distant places[32]. This phenomenon aligns with the second law of thermodynamics, where urban systems permanently export entropy to other ecosystems while increasing their internal complexity[33].

Material appropriation is a metabolic process that can be described as a vector of material and energy between short- or long-distance ecosystems (Fig. 1), spanning from landscape to global scales[7]. Industrialization has profoundly transformed contemporary appropriation capacities through the sustained injection of fossil fuels, thus extending the UM up to the planetary scale[34][35]. Currently, even most elemental inputs, such as food and water, are increasingly sourced from distant locations[34]. Material appropriation generates uncountable social, economic, and ecological effects in distant locations, often through extractive processes without explicit links to direct urban commanding actors. These effects pose significant challenges for the conceptualization and quantification of UM, because the current knowledge of the dynamics of goods and processes that societies develop and maintain remains marginal and insufficient to fully understand the metabolic dimension[11]. Consequently, the logic of material appropriation and reproduction, with its ecological-economic duality, is often obscured[8].

Urban systems are entangled with other ecosystems to maintain the material and energy flows that are vital for their organization and structure, regardless of the kind of materials being appropriated. While materials and energy flows are normally acknowledged, the inverse information flows (e.g., money) are not accounted for. Every material flow implies a specific inverted monetary flow (high level of information that allows agents to take decisions) and also waste

① World-systems theory understands human interaction integrating economic, political, and social dimensions in a multi-scalar manner that assesses the regional linkages using the world as a unit of analysis (source: Ref. [31]).



1. Appropriation of natural capital under a landscape perspective: conceptualization of spatial links in the metabolic fluxes of gas and timber as examples.

flows as a consequence of the second law of thermodynamics. Material input is a vector linking source ecosystems with urban centers, which has been analysed as teleconnections, acknowledging the relevance of distant connections for land use changes[36][37]. Distant connections are, therefore, a fundamental component of an enlarged UM. This metabolic entanglement can be unveiled using an ecosystem approach.

3.2 Rethinking Urban Systems as Ecosystems Composed of Biomass and Technomass

The "ecosystem" concept is an analytical tool linking current isolated UM studies[38][39]. Understanding urban systems as ecosystems incorporates the knowledge of ecology, integrating ecological processes into urban analyses and allowing transdisciplinary feedback[4]. Among different types of ecosystems, urban ecosystems are special as their processes are led and shaped by human decisions[40]. Urban ecosystems are coupled socio-ecological systems with tremendous biophysical complexity and spatio-temporal heterogeneity heavily concentrated over relatively short distances. Urban areas consist of highly spatially structured mosaics of built, planted, and managed habitats; relic and emergent "natural" areas; and habitats that are hybrids of constructed and biophysical elements. The spatial constituents of the urban mosaics vary in size and can be understood as individual ecosystems. At a higher spatial scale, dense villages, cities, suburbs, exurbs, and towns constitute ecosystems[41][42]. Therefore, the "urban ecosystem" should encompass all material components, in the form of biomass and technomass, as fundamental interlinked elements of the built environment[7].

In contrast to biomass, "technomass" is defined as the aggregated sum of processed materials (per unit of surface and time) that have been transformed by human labor to be consumed by society or accumulated as physical stocks[22][43]—here labor can be seen as an organic purposive metabolic process similar to other organic and non-organic agents[5], and an appropriation of what exists in nature for the requirements of humans[44]. Technomass is the direct outcome of labor and a transformed nature that embodies labour assuming a "thing-like" form—i.e., commodity—which is iteratively involved in spiralling subsequent material assemblages[5].

To distinguish urban ecosystems from the other ones, the material structure and productivity of ecosystems can be examined[4][7][22]. From a material perspective, while native ecosystems accumulate biomass, urban ecosystems accumulate technomass[7]. Both are fundamental indicators of UM. Rates of material accumulation in native ecosystems, i.e., accumulation of biomass through net primary production (NPP) are fundamental to understanding metabolic behaviors to communicate and summarise to what extent development paths are healthy[4][7].

In urban ecosystems, technomass rather than biomass is predominant, determining its body, i.e. the very ecosystem's material structure. The material accumulation shapes specific urbanization patterns[7]. From the operational perspective, the respective shares of biomass and technomass provide a powerful description of a broad spectrum of ecosystems with different degrees of urbanization with continuous analysis rather than categorical analysis[7]. Furthermore, the material structure emerging from UM is a study object in disciplines related to urban planning and design, as well as landscape architecture. This conceptual link can be helpful to promote sustainable urban development, deepening the understanding of the particular metabolism of urban forms and settlement patterns[45]~[50].

3.3 An Ecosystem Approach to UM

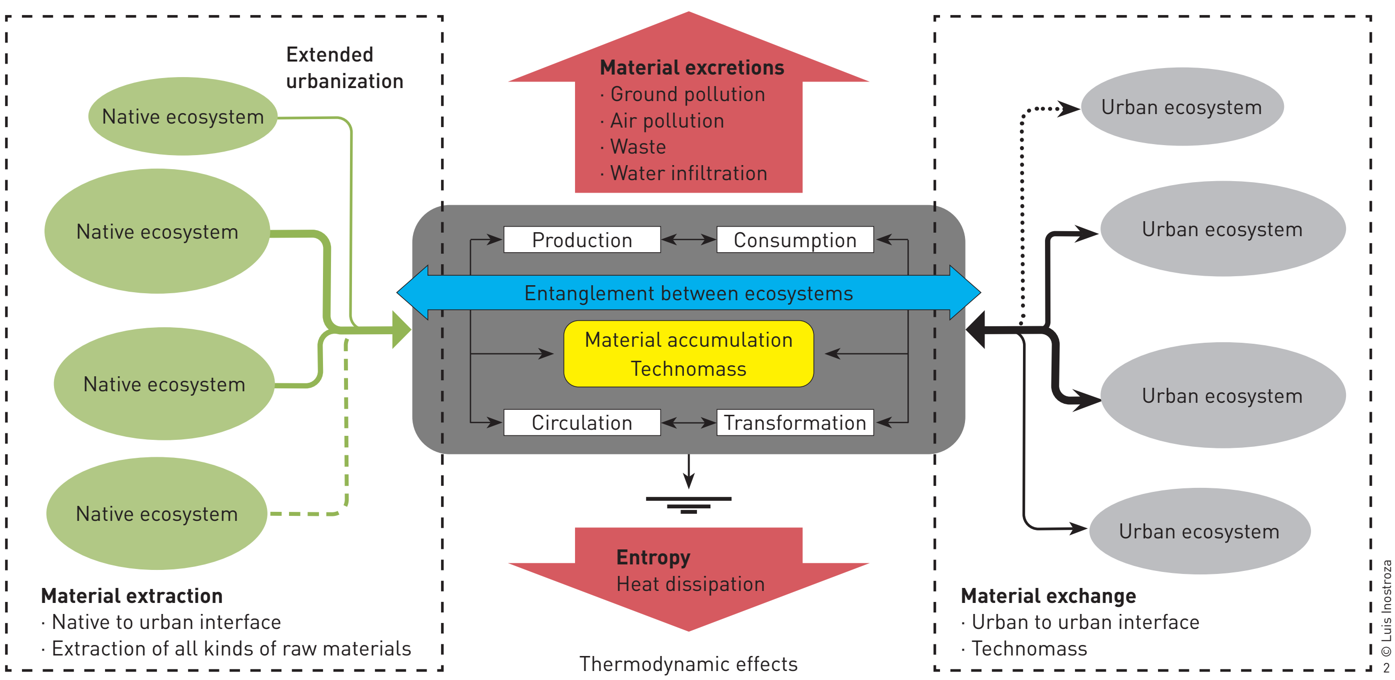
UM is a fundamental process that structures urban organization. Analysing UM through an ecosystem approach helps understand cities and landscapes as dissipative structures, rather than organisms, where the flows of matter, energy, and information follow certain regularities that can be scientifically examined. An ecosystem approach to UM means using the tools of ecology to conceptualize and operationalize the analysis of urban systems[4].

UM ecologically and economically links varied ecosystems along a differentiated gradient by their material intensity, as biomass and technomass[7]. UM framed the spatio-temporal relationship between different ecosystems at the landscape scale. The metabolic vortex involves the urban ecosystem, the built environment, the very core of industrial society, a poli-nucleated built space in permanent expansion, sustaining its development with direct metabolic fluxes from other ecosystems[14]. This means that, town and country form an indissoluble, metabolically entangled binomial, as it was understood by Sir Patrick Geddes, the founding father of town planning, in Cities in Evolution[51].

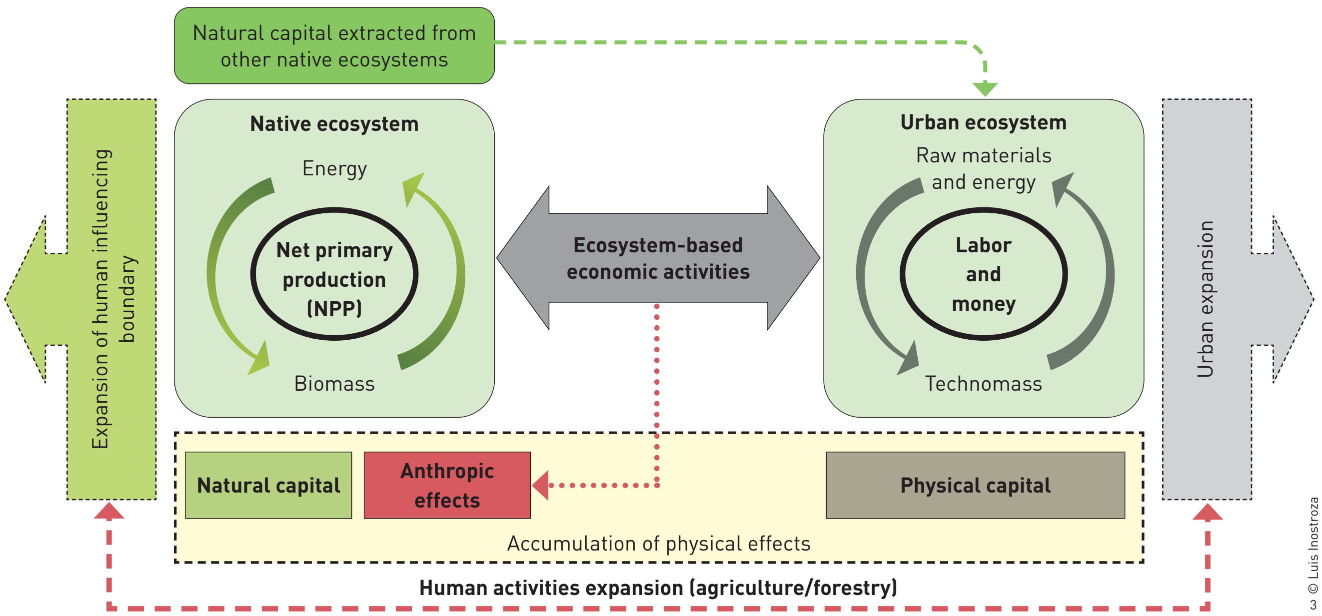
3.4 Entangled UM

UM links different ecosystems, urban and native, through material and energy exchanges during what is called here UM entanglement. UM produces effects along two axes (Fig. 2). Firstly, the horizontal axis (*x*-axis) describes the teleological/purposive relationships. It delineates the material interactions between various ecosystems, encompassing those from the external native ecosystems to urban ecosystems and those between urban ecosystems. All kinds of raw materials originate from native ecosystems. The *x*-axis also addresses the appropriation (input) and the purposive output, where technomass forms diverse assemblages that makes urban systems growing material structures[7]. The *x*-axis links UM to the metabolism of other urban and native ecosystems across extensive distances via teleconnections[36], integrating human and natural systems[52]; and determines the magnitude of material exchanges between urban and native ecosystems, setting conditions for landscape based circularities. Secondly, the vertical axis (*y*-axis) illustrates the endogenous and exogenous impacts of UM, representing the non-purposive outcomes dictated by the laws of thermodynamics—the material excretions (e.g., pollution) and entropy (e.g., heat). Technomass production, central to UM, forms the material structure of urban ecosystems, underpins the metabolic–purposive links to other ecosystems, and determines the intensity and the magnitudes of undesired excretions as a function of the material size of urban systems—the larger the material size of the city, the larger will be the excretions. Technomass will transit elsewhere to continue the production chain or to be finally consumed likely in faraway distances evidencing the dramatically large horizontal nature of UM at the planetary scale[8]. This is an allometric, metabolic regularity of urban systems determined by the laws of thermodynamics, posing a fundamental challenge to the physical expansion of cities.

The entanglement of technomass and biomass shows a distinctive spatial behavior, where the underlying driving forces



2. An entangled UM conceptualizes urban ecosystems linked to other native and urban ecosystems following the laws of thermodynamics (green and black arrows represent the effects on *x*-axis, red arrows represent the effects on *y*-axis).



3. An example of the entanglement between the Patagonian steppe ecosystem and the urban ecosystem of Punta Arenas, Chile.

of urban expansion and densification are to be found (Fig. 3). These two spatial processes define urban ecosystems as growing structures. Urban expansion and densification have been largely analysed and measured in urban research in 2D analysis. However, both those processes imply an increase in the urban material stock that has not been explicitly acknowledged. Technomass unveils the entanglement of material structures with distant landscapes in terms of production and functioning[53]. The entanglement also produces spatial effects in other ecosystems, as exemplified in the expansion of the livestock boundary (Fig. 3). Three spatial effects can be derived from biomass extraction through animal husbandry: the reduction of the forest ecosystem, urban expansion, and densification of the existing urban tissue. The spatial effect of urban expansion has been identified at local scale[54], while also has been globally observed[55].

Urban ecosystems perform a particular material productivity by producing stocks of technomass, which underpin their material structure. The studies of technomass production, involving uncountable economic activities, can reveal their metabolic role[5][43]. Most artefacts traded today fall into one of the categories used to analyse and measure technomass. Applying the technomass concept to analyse UM brings the material production of urban ecosystems, particularly material assemblages embodying complex socio-metabolic forces, to the forefront of urban analysis[22]. Technomass production sustains large and complex material chains, which nurtures urbanization across the world[8]. Matter entering the metabolic process, consisting of all products used in production, is already a configured material assemblage[5].

4 Conclusions

Understanding the consumption, transformation, and accumulation of materials and energy by UM is crucial for sustainable urban development. Using technomass reduces the uncertainty of global top-down models, unveiling the metabolic links between ecosystems, where urban ecosystems are always appropriating matter and energy from other ecosystems. Such appropriation is facilitated by technomass, as all entities in the planetary space of flows are interconnected through material infrastructure.

Technomass serves as an indicator that links landscape analysis of urban expansion and densification with UM studies of material flows dynamics. Sustainable urban development requires closed material and energy cycles, that can eventually imply the reduction of the horizontal scope of material exchanges towards landscape-based circularities. Transdisciplinary integration between design and planning disciplines that shape urban environments and UM assessments can be realized through applying technomass.

ACKNOWLEDGEMENTS

This article is an extract of the author's habilitation thesis defended at the Ruhr University Bochum. The author expresses sincere gratitude to Prof. Dr. Harald Zepp for his invaluable mentoring during the development of these ideas.

Competing interests | The author declares that he has no competing interests.

REFERENCES

[1] Broto, V. C., Allen, A., & Rapoport, E. (2012). Interdisciplinary Perspectives on Urban Metabolism. *Journal of Industrial Ecology*, 16(6), 851–861.

[2] Zhang, Y. (2013). Urban metabolism: A review of research methodologies. *Environmental Pollution*, (178), 463–473.

[3] Decker, E. H., Elliott, S., Smith, F. A., Blake, D. R., & Rowland, F. S. (2000). Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment*, (25), 685–740.

[4] Golubiewski, N. (2012). Is there a metabolism of an urban ecosystem? An ecological critique. *Ambio*, 41(7), 751–764.

[5] Swyngedouw, E. (2005). Metabolic Urbanization: The Making of Cyborg Cities. In: N. Heynen, M. Kaika, & E. Swyngedouw (Eds.), *In the Nature of Cities: Urban Political Ecology and the Politics of Urban Metabolism* (pp. 36–55). Routledge.

[6] Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The Changing metabolism of cities. *Journal of Industrial Ecology*, 11(2), 43–59.

[7] Inostroza, L. (2018). The circularity of the urban ecosystem material productivity: The transformation of biomass into technomass in Southern Patagonia. *Sustainable Cities and Society*, (39), 335–343.

[8] Inostroza, L., & Zepp, H. (2021). The metabolic urban network: Urbanisation as hierarchically ordered space of flows. *Cities*, (109), 103029.

[9] Toledo, V., Alarcón-Cháires, P., & Barón, L. (2002). *La Modernización Rural de México: Un Análisis Sociológico*. Secretaría de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología, Universidad Nacional Autónoma de México.

[10] Huang, Q., Zheng, X., Liu, F., Hu, Y., & Zuo, Y. (2018). Dynamic analysis method to open the “black box” of urban metabolism. *Resources, Conservation and Recycling*, (139), 377–386.

[11] Baccini, P., & Brunner, P. H. (2012). *Metabolism of the Anthroposphere. Analysis, Evaluation, Design*. The MIT Press.

[12] Inostroza, L. (2022). Biodiversity and Region: A Unitary System. The Paradigm Shift in 21st Century Urban Development. In: M. A. Mejia & J. D. Amaya-Espinel (Eds.), *BiodiverCities by 2030. Transforming Cities with Biodiversity* (p. 431). Instituto de Investigaciones de Recursos Biologicos Alexander von Humboldt.

[13] von Thünen, J. H. (1966). *von Thünen’s Isolated State: An English Edition of Der Isolierte Staat*. Pergamon Press.

[14] Antequera, J. (2004). *El Potencial de Sostenibilidad de los Asentamientos Humanos*. Caixa de Sabadell.

[15] Rueda Palenzuela, S. (2002). Modelos Urbanos y Sostenibilidad. *I Congreso de Ingeniería Civil, Territorio y Medio Ambiente* (pp. 23–48). Colegio de Ingenieros de Caminos Canales y Puertos.

[16] Jacobs, J. (1972). *The Economy of Cities*. Penguin Books Ltd.

[17] Sahlins, M. (1972). *Stone Age Economics*. Aldine·Atherton, Inc.

[18] Smith, M. E. (2015). From prehistoric villages to cities: Settlement aggregation and community transformation by jennifer birch, ed. *American Anthropologist*, 117(1), 178–179.

[19] Moore, J. W. (2015). *Capitalism in the Web of Life. Ecology and the Accumulation of Capital*. Verso.

[20] Bunge, M. (1963). A general Black Box Theory. *Philosophy of Science*, 30(4), 346–358.

[21] González de Molina, M., & Toledo, V. M. (2014). *The Social Metabolism: A Socio-Ecological Theory of Historical Change*. Springer.

[22] Inostroza, L. (2014). Measuring urban ecosystem functions through ‘Technomass’—A novel indicator to assess urban metabolism. *Ecological Indicators*, (42), 10–19.

[23] Wiedenhofer, D., Steinberger, J. K., Eisenmenger, N., & Haas, W. (2015). Maintenance and expansion: Modeling material stocks and flows for residential buildings and transportation networks in the EU25. *Journal of Industrial Ecology*, 19(4), 538–551.

[24] Brunner, P. H., & Rechberger, H. (2017). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. CRC Press.

[25] Goldstein, B., Birkved, M., Quitzau, M.-B., & Hauschild, M. (2013). Quantification of urban metabolism through coupling with the life cycle assessment framework: Concept development and case study. *Environmental Research Letters*, 8(3), 035024.

[26] Duro, J. A., Perez-Laborda, A., Löw, M., Matej, S., Plank, B., Krausmann, F., Wiedenhofer, D., & Haberl, H. (2024). Spatial patterns of built structures co-determine nations’ level of resource demand. *Journal of Industrial Ecology*, 28(2) 289–302.

[27] Maturana, H., & Varela, F. (1994). *De Maquinas y Seres Vivos. Autopoiesis: La Organizacion de lo Vivo*. Editorial Universitaria.

[28] Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *PNAS*, 114(8), 1880–1885.

[29] Lemoine-Rodríguez, R., Inostroza, L., & Zepp, H. (2020). The global homogenization of urban form. An assessment of 194 cities across time. *Landscape and Urban Planning*, (204), 103949.

[30] Wentz, E. A., York, A. M., Alberti, M., Conrow, L., Fischer, H., Inostroza, L., Jantz, C., Pickett, S. T. A., Seto, K. C., & Taubenböck, H. (2018). Six fundamental aspects for conceptualizing multidimensional urban form: A spatial mapping perspective. *Landscape and Urban Planning*, (179), 55–62.

[31] Kardulias, P. N. (2008). World systems theory. *Encyclopedia of Archaeology*, 2219–2221.

[32] White, D. F., & Wilbert, C. (2009). *Technonatures. Environments, Technologies, Spaces, and Places in the Twenty-first Century*. Wilfrid Laurier University Press.

[33] Prigogine, I., & Stenger, I. (1984). *Order Out of Chaos. Man’s New Dialogue With Nature*. Bantam Books.

[34] Fischer-Kowalski, M. (1998). Society’s metabolism. *Journal of Industrial Ecology*, 2(1), 61–78.

[35] Harvey, D. (1996). Cities or urbanization?. *City: Analysis of Urban Trends, Culture, Theory, Policy, Action*, 1(1–2), 38–61.

[36] Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D.,

Langanke, T., Marcotullio, P., Munroe, D. K., Olah, B., & Simon, D. (2012). Urban land teleconnections and sustainability. *PNAS*, 109(20), 7687–7692.
[37] Liu, J., Hull, V., Batistella, M., Defries, R., Dietz, T., Fu, F., Hertel, T. W., Cesar, R., Lambin, E. F., Li, S., Martinelli, L. A., Mcconnell, W. J., Moran, E. F., Naylor, R., Ouyang, Z., Polenske, K. R., Reenberg, A., de Miranda Rocha, G., Simmons, C. S., Verburg, P. H., Vitousek, P. M., Zhang, F., & Zhu, C. (2013). Framing sustainability in a telecoupled world. *Ecology and Society*, (18)2, 26.
[38] Newell, J. P., & Cousins, J. J. (2015). The boundaries of urban metabolism: Towards a political-industrial ecology. *Progress in Human Geography*, 39(6), 702–728.
[39] Wachsmuth, D. (2012). Three ecologies: Urban metabolism and the society-nature opposition. *Sociological Quarterly*, 53(4), 506–523.
[40] Pickett, S. T. A., Burch, W. R. J., Dalton, S. E., Foresman, T. W., Grove, J. M, & Rowntree, R. A. (1997). A conceptual framework for the study of human ecosystems in urban areas. *Urban Ecosystems*, (1), 185–199.
[41] McGrath, B., & Pickett, S. T. A. (2011). The metacity: A conceptual framework for integrating ecology and urban design. *Challenges*, 2(4), 55–72.
[42] McGrath, B., & Shane, G. (2017). Metropolis, Megalopolis and Metacity. In: C. G. Crysler, S. Cairns, & H. Heynen (Eds.), *The Sage Handbook of Architectural Theory* (pp. 641–657). SAGE.
[43] Hornborg, A. (2001). *The Power of the Machine: Global Inequalities of Economy, Technology, and Environment*. AltaMira Press.
[44] Marx, K. (1887). *Capital: A Critique of Political Economy* (Vol. I). Progress Publishers.
[45] Dar, M. A., Raina, R., Singh, R., Kaur, S., Singh, H. P., & Batish, D. R. (2023). Role of Sustainable Urban Metabolism in Urban Planning. In: R. Bhadouria, S. Tripathi, P. Singh, P. K. Joshi, & R. Singh (Eds.), *Urban Metabolism and Climate Change* (pp. 151–169). Springer.
[46] Galan, J., & Perrotti, D. (2019). Incorporating metabolic thinking into regional planning: The case of the Sierra Calderona Strategic Plan. *Urban Planning*, 4(1), 152–171.
[47] Otero Peña, D., Perrotti, D., & Mohareb, E. (2022). Advancing urban metabolism studies through GIS data: Resource flows, open space networks, and vulnerable communities in Mexico City. *Journal of Industrial Ecology*, 26(4), 1333–1349.
[48] Perrotti, D. (2022). Toward an agentic understanding of the urban metabolism: A landscape theory perspective. *Urban Geography*, 43(1), 1–11.
[49] Perrotti, D., & Stremke, S. (2020). Can urban metabolism models advance green infrastructure planning? Insights from ecosystem services research. *Environment and Planning B: Urban Analytics and City Science*, 47(4), 678–694.
[50] Pistoni, R., & Bonin, S. (2017). Urban metabolism planning and designing approaches between quantitative analysis and urban landscape. *City, Territory and Architecture*, (4), 20.
[51] Geddes, P. (1915). *Cities in Evolution: An Introduction to the Town Planning Movement and to the Study of Civics*. Williams.
[52] Liu, J., Dietz, T., Carpenter, S. R., Taylor, W. W., Alberti, M., Deadman, P., Redman, C., Pell, A., Folke, C., Ouyang, Z., & Lubchenco, J. (2021). Coupled human and natural systems: The evolution and applications of an integrated framework. *Ambio*, (50), 1778–1783.
[53] Soonsawad, N., Marcos-Martinez, R., & Schandl, H. (2024). City-scale assessment of the material and environmental footprint of buildings using an advanced building information model: A case study from Canberra, Australia. *Journal of Industrial Ecology*, 28(2), 247–261.
[54] Dawazhaxi, Zhou, W., & Cao, J. (2022). Integrating 2-D built-up and 3-D technomass reveals the continuity and hybridity of urban-rural gradient. *Sustainable Cities and Society*, (87), 104217.
[55] Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in Planning*, 75(2), 53–107.

https://doi.org/10.15302/J-LAF-1-030053 收稿日期 | 2023-07-28 录用日期 | 2024-04-01 中图分类号 | TU986 文献标识码 | B

通过应用技术量实现城市新陈代谢与景观学科的融合

路易斯·伊诺斯特罗萨[1,2,*]

***通讯作者邮箱：** luis.inostroza@mendelu.cz

1 捷克布尔诺孟德尔大学区域发展与国际研究学院，布尔诺市 613 00
2 智利自治大学研究与博士项目副校长办公室，圣地亚哥 7500912

摘要

城市新陈代谢为分析城市发展及其影响提供了一个强有力的框架。然而，部分理论和操作层面上的不足限制了城市新陈代谢在理解城市整体过程中的应用，阻碍了其在设计和规划工作中潜在效益的转化。本文基于跨学科视角，系统分析了当前的城市新陈代谢模型并指出了四项不足之处：1）采用“孤立状态”手段将城市系统与其他生态系统相隔离；2）忽略了城市系统的内部过程，即“黑箱悖论”；3）依赖线性物质思维，关注于单一物质的流动路径；4）忽视了城市系统的物质生产力，即进入系统的能量和物质会被用于城市物质结构的再生产，以及商品和可交易物品的生产。尽管现有文献中已有对这些问题的专项研究分析，但鲜有整体性研究。本文提出了一种提升城市新陈代谢分析的方式——通过应用“技术量”的生态系统途径解决上述不足，并在景观设计和规划学科中切实践行，以促进可持续城市发展。

关键词

城市新陈代谢；技术量；城市生态；生态系统途径；新陈代谢通量

文章亮点

- 分析了当前城市新陈代谢模型的四大不足之处
- 重新思考城市系统，将其视为由生物量和技术量共同构成的生态系统
- 提出通过生态系统途径促进城市新陈代谢和景观学科的融合

编辑 高雨婷，田乐