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ANAS TUFFAHA

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THE ROLE OF GREEN INFRASTRUCTURE FOR URBAN METABOLISM IN AMMAN

Spatializing Urban Metabolism: A Framework for Flow Resilience and Spatial Justice

THESES OF DOCTORAL DISSERTATION

ANAS TUFFAHA

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Name: **Hungarian University of Agricultural and Life Sciences**

Doctoral School: Doctoral School of Engineering Sciences,

Field: Engineering Sciences

Branch: Agricultural Engineering Sciences

Program: Landscape Architecture and Landscape Ecology

Head of the Doctoral School: **Dr. László Bozó**
University professor, DSc, MHAS
MATE University
Department of Soil Science Water Management

Supervisor: **Dr. Ágnes Sallay**
University professor, PhD
MATE University
Department of Landscape Planning and Regional Development

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Approval of the Head of Doctoral School

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Approval of the Supervisor

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1. RESEARCH BACKGROUND

Cities are dynamic, living systems that continuously consume, transform, and leave resources and materials as outcomes. This process has been conceptualized as Urban Metabolism (UM). This framework moves beyond viewing cities as static collections of buildings, instead analyzing the complex flows of energy, water, materials, and information that sustain urban life and produce waste.

Traditionally UM focuses on quantitative efficiency and material flow analysis which shape and explain the role of UM as one of many urban sustainability concepts. While through recent literature and current contemporary UM trends it seeks to understand how these flows shape and are shaped by different elements, in addition to its relation to indirect flows and socioeconomic aspects. This research focuses on these elements, by looking at the urban form, climate, human well-being and codes or regulations as indirect flows.

Through the research, another element is put under the lens within this metabolic system, a part of a direct flow that is connected to many other important flows, Green Infrastructure (GI) (including parks, street trees, green corridors, and vegetated surfaces) which holds a uniquely influential position. Besides being a main focal point of my study, and although it constitutes only a part of the broader biotic flow, GI intersects with nearly every major urban metabolic process. Unlike single-purpose grey infrastructure, GI simultaneously moderates microclimates, reduces energy demand for cooling, improves air and water quality, enhances biodiversity, and supports walkability and mental health.

The crossflow capacity makes GI not merely an ecological amenity, but an interesting element within UM, that has the capability to aid its incomes and outcomes balance, with its ability to also serve as a diagnostic aspect for assessing urban performance. While also testing its relation to urban efficiency, and equity.

This research positions GI as an applied diagnostic instrument within UM. It argues that the spatial distribution, quality, and performance of GI can reveal deeper metabolic flows conditions, such as inefficiencies, environmental vulnerabilities, temporal changes or climatic incidents, and socio-spatial injustices.

By focusing on GI, and its relation to metabolic flows but also some indirect flows, the study develops a multi-method toolkit including microclimatic simulation, street-level profiling, species-level assessment, and policy analysis, to translate complex metabolic flows into operational knowledge for planners and designers.

The heart of this investigation is Amman, Jordan. As a rapidly growing capital in an arid region, Amman faces acute challenges: severe water scarcity, intense urban heat, fragmented governance, and pronounced socio-spatial divides.

These unique elements that are not all evident in many popular urban metabolism studies that took place in central Europe or north America create a stark metabolic profile where resource flows are strained and unevenly distributed. The scarcity and unequal access to GI in Amman amplify environmental burdens, making the city an ideal prototype for testing how GI-based diagnostics can uncover both ecological and social metabolic imbalances. The choice of the city lies in its weaker GI distribution, scarce resources, and extreme temperature which might give more insights on the flows put under the lens as mentioned.

To sum things up, the dissertation examines the interconnected relationship between UM, GI (a main flow), and spatial justice (indirect flows). It investigates how GI functions and aids to diagnose metabolic disparities and how metabolic insights, in turn, can guide the equitable design and placement of GI. By spatializing UM at the neighborhood and street scale.

The research aims to provide a replicable framework and even possibilities for any future guidelines or interventions that can help in fostering more resilient, just, and metabolically aware urban futures, particularly in resource-constrained cities like Amman which have very little amount of research regarding UM and GI or spatial justice.

2. RESEARCH QUESTIONS AND OBJECTIVES

This study is guided by a sequence of interconnected research questions, each connected to an aim and research objectives that are addressed to tackle throughout the dissertation.

2.1 Research Questions

RQ1: What gaps or limitations within the historical and contemporary evolution of UM literature have surfaced? What has led to the neglect of socio-spatial and socio-economic dimensions?

Through a critical review of UM literature, the study examines how the efficiency-oriented origins of UM produced blind spots focusing mostly on qualitative aspects, while spatial equity, neighborhood disparities, and the lived experience of people as an indirect metabolic flow isn't often addressed which this dissertation seeks to address.

RQ2: What is the relationship between UM and GI, and how do their interactions shape metabolic performance in cities?

UM is a complex multi-flow system, with Gi being part of it. Investigating their relationship at a global scale requires massive datasets. Therefore, this research focuses on Amman, where aridity, low vegetation, and spatial inequity make GI–UM interactions particularly visible and critical.

RQ3: How can GI-enabled diagnostic tools (e.g., microclimatic simulation, street-level imagery, species-level metabolic assessment) and UM flow analysis inform each other in evaluating metabolic performance?

This question investigates the **bidirectional relationship**, like how Metabolic analysis reveals where GI is needed, GI interventions modify metabolic outcomes or even how Improvements in GI affect microclimate, carbon, walkability, and equity, and in general the ability to use UM findings to refine GI placement and design priorities.

RQ4: What is the relationship between socio-economic conditions,

spatial justice, governance patterns, and metabolic flows in Amman, and how do these factors influence GI distribution and performance?

This question examines how zoning, land value disparities, income-based separation, and neighborhood form shape metabolic inequities, patterns that are strongly visible in Amman's east–west divide, water scarcity, and environmental burdens.

RQ5: How can the multi-method GI-based metabolic tools in this dissertation support evidence-based planning and decision-making in Amman?

2.2 Research Objectives

Objective 1, Critical Literature Diagnosis. To conduct a systematic review of UM literature to identify historical and methodological gaps, particularly the neglect of indirect flows like socio-spatial equity and lived experience.

Objective 2, Conceptual Integration. To clarify and operationalize the conceptual relationship between UM and GI, positioning GI as an analytically useful, crossflow diagnostic instrument.

Objective 3, Multi-Method Toolkit Development. To design and validate a diagnostic toolkit that integrates street-scale profiling, microclimatic simulation, species-level assessment, and spatial-equity.

Objective 4, Empirical Diagnosis in Amman. To apply the toolkit to multiple neighborhoods in Amman and map metabolic performance, identify environmental burden hotspots, and document socio-spatial correlations.

Objective 5, Interpretation of Governance/ Socioeconomic Drivers. To analyze how zoning, land value, governance, and socio-economic patterns shape metabolic inequalities and GI distribution in Amman.

Objective 6, Prescriptive Synthesis and Policy Translation. To synthesize diagnostic results into practical recommendations for GI placement, species selection, policy, and strategic intervention priorities.

3. MATERIALS AND METHODS

The methodology is structured by operationalizing GI within UM, auditing spatial form, measuring metabolic performance, neighborhood outcomes, and analyzing disparities through governance as follows:

1. **Street-Scale Metabolic Profiling (SVI):** Uses Google Street View imagery and pixels to quantify perceived greenery, enclosure, and hardscape at pedestrian level. Translating lived experience into a spatial metric for the 'People' flow.
2. **Microclimatic Simulation (ENVI-met):** Applies 3D fluid dynamics modeling to simulate how GI/urban forms configuration affect potential air temperature, vapor flux, and CO_2 exchange. It quantifies the 'Climate' and 'Energy' flow in design scenarios.
3. **Tree Species as Metabolic Agents:** Using ENVI-met to compare species-specific performance, linking tree selection directly to measurable metabolic outcomes and urban design decisions by focusing on cooling, water use, and carbon exchange.
4. **Neighborhood-Scale Metabolic Assessment:** Changes the scale of UM applications to neighborhood level analysis which Synthesizes data, simulations, and surveys in Amman districts across UM flows (Biota, Climate, Water, Energy, Materials, People, Goods) as comparative metabolic performance scores.
5. **Policy & Spatial Justice Analysis:** By studying zoning codes, land value maps, NDVI data, and resident surveys to trace how regulatory frameworks precondition the distribution of GI and metabolic burdens and understand their interconnection.

Table 3.1: Summary of the Tools

Tool	UM Flow Addressed	Key Output	Analytical Contribution to UM
Street View (SVI)	People, GI, Materials	Green View Index, street ratio composition	Translates lived views to indicators. greenery, enclosures, street ratios.

Microclimatic Simulation	GI, Climate, Energy, Water	Potential Air Temp.(PAT), Vapor/CO_2 Flux, Scenario testing	Quantifies the thermal and atmospheric effects of urban form and GI, to linking spatial design to measurable metabolic outcomes.
Species Analysis	GI, Climate, Energy, Water	Species-specific selection, cooling & water-use efficiency	Treats vegetation as an active metabolic agent, distinguishing species-specific cooling capacity, water demand, and carbon exchange.
Neighbor-hood Assessment	All (Synthetic)	Comparative urban metabolic score (1-10) and analysis	Provides a holistic metabolic profile of neighborhoods
Policy & Justice Analysis	Governance, Spatial Justice, GI, People	policy-performance gaps, disparity ratios, support planning/strategy	Links observed disparities to zoning, land value, and institutional decision-making.

The tools build on the literature review as well as gaps identified within it, such as the focus on biophysical flows at the expense of socio-spatial equity and human-scale experience, or the growing UM studies with priorities to find hotspots and create intervention points from analysis.

As seen in table above, after the literature review, the methods begin with a spatial audit, where Street View Imagery maps the existing distribution of GI and decode its regulatory context then the simulations and species-specific analysis quantify the thermal and atmospheric performance of the audited urban fabric. Next, the neighborhood-scale assessment synthesizes these data into a holistic metabolic profile for each district. Finally, policy and spatial justice analysis give explanations by linking diagnosed disparities to underlying drivers such as zoning and land value aiding the understanding of the interconnection between UM, GI and Spatial justice.

This method looks at Amman as the lab site, UM as the testing concept, its flows direct/indirect as the criteria, and GI as the main flow focused on.

4. NEW SCIENTIFIC RESULTS (THESES)

This chapter consolidates the original contributions of the dissertation into a series of formal theses. Each thesis presents a scientific finding that advances the theory and practice of UM.

6.1 Thesis 1: Urban Metabolism literature shows it largely operates at technical scales, limiting its ability to capture spatial and personal urban experience as a critical gap. The findings also demonstrate that applying UM at the neighborhood scales presented strengthens its diagnostic capacity by revealing human-scale and spatial inequalities masked by total averages.

This thesis is grounded in both, the structured literature review conclusion which is an essential part of the dissertation, and the empirical results developed across Chapters 4. The meta-analysis of highly cited Urban Metabolism studies demonstrated a persistent emphasis on material, energy, and quantified flows at city or metropolitan scales, with limited operationalization of spatial differentiation or lived experience (spatial and socio-economic dimensions). While this limitation has been hinted by scholars such as Kennedy, it has rarely been addressed.

This dissertation responds to that gap by shrinking the analytical scale rather than expanding flow complexity. Through neighborhood-level metabolic assessment in Amman presented in Chapter 4.3, the research demonstrates how metabolic conditions vary sharply within the same city unlike having one final average of incomes and outcomes of the city as a metabolic result.

The results in 4.3 show that neighborhoods with similar aggregate urban characteristics exhibit fundamentally different performances once spatial configuration, greenery, surface materials and pedestrian experience are examined. Districts that are adjacent to each other showcase different results when it comes to cleanliness, waste, energy awareness, permeable surfaces, GI quality and distribution, NDVI, potential air temperature, walkability, air quality, traffic and goods distribution as a flow.

The findings show that spatial justice and its distributions are viewed on localized scales, showing heat stress, walkability deficits, and uneven access to GI. By integrating perceptual indicators, survey responses and neighborhood / district level analysis, essential for interpreting how metabolism functions for different urban populations.

The findings are operationalizing perceptual, spatial, and socio-economic dimensions which are limited in applications, alongside biophysical flows, extending Urban Metabolism from a system-level accounting framework into a spatially and socially legible urban sustainability tool.

6.2 Thesis 2: Findings demonstrate that street profiling like Street View Imagery extends Urban Metabolism to a lived perception level by capturing spatial, vertical, and material dimensions (ratios) of urban environments that are invisible to top-down methods. Since the findings also show measurable environmental performance and subjective human perception do not always align in a paradoxical relation, aiding diagnostics for experiences in everyday urban life.

This thesis builds on the development of the Street-Scale Metabolic Profiling method using Street View Imagery. Traditional Urban Metabolism approaches rely on aggregated, top-down indicators that quantify biophysical flows but overlook how these conditions are perceived on the ground. These traditional flows, which are the basics of UM and undeniably core and important methods, can also integrate human perception, which is a very complex subject.

The complexity is presented in the findings and results of subchapters 4.3 and 4.4 where survey results revealed a counterintuitive pattern: in higher income neighborhoods with relatively more developed GI and cleaner streets reported dissatisfaction with greenery and cleanliness. Conversely, in low-income, GI-deprived neighborhoods, residents expressed satisfaction, despite objectively poorer conditions.

This thesis demonstrates that people as a flow is a multidimensional concept, incorporating both quantitative urban metabolic measurements and subjective resident perception. Therefore, it cannot be understood solely through physical metrics, perception, expectation, and context play a decisive role in how metabolic conditions are experienced.

Street-scale metabolic profiling does not resolve this paradox, but it makes it visible and analyzable. By aligning perceptual conditions with measurable spatial characteristics, the method provides Urban Metabolism with a missing diagnostic layer. In summary, there is a link between biophysical performance and lived experience. In doing so, it strengthens the capacity of Urban Metabolism to address spatial justice and human-centered sustainability without replacing or undermining its quantitative foundations.

6.3 Thesis 3: Through my application of high-resolution microclimatic simulations in Amman and a few in Budapest, I establish that urban climate as a main UM flow can be transformed from a passive, analyzed flow into a diagnosable and actively designable component of the urban metabolic system that is proactively engineered.

The thesis results are grounded in the extensive analysis of UM flows and climates direct responsive relation to spatial design, surface materials, and GI configuration since GI is a main element of this dissertation. This is also verified throughout the ENVI-met simulations conducted in Amman subchapter 4.2.1 microclimatic simulations in 2 neighborhoods showcasing different interventions, and subchapter 4.3 with 4 neighborhood simulations, in addition to a small interventional simulation done in Budapest in subchapter 4.2.3.

Climate has always been treated as a fundamental flow in UM, yet it is often examined at broad scales through meteorological or climatological studies, leaving neighborhood- and street-level microclimates insufficiently analyzed. The results prove that we can proactively engineer the atmospheric conditions of city blocks by quantifying how specific choices directly recalibrate thermal flows and energy demand from a metabolic perspective.

Rather than treating climate as a static external input, the simulations quantified how specific interventions, such as reducing asphalt coverage, introducing courtyard typologies, or adding green pockets, unbuilt areas, adding greenery rows and certain numbers of trees, alter air temperature, heat stress, and cooling demand. The results demonstrate that form or green infrastructure directly shape climatic flows, making them diagnosable and designable components of the urban metabolic system. By integrating microclimatic simulation into Urban Metabolism, this research strengthens the framework's capacity to link spatial design choices with energy, comfort, and resilience outcomes.

These findings validate microclimatic simulation as an indispensable diagnostic tool for urban metabolism. Just as material flow analysis measures energy or waste, simulation allows climate flow to be quantified in response to design interventions.

6.4 Thesis 4: My repeated ENVI-met simulations across Amman's neighborhoods demonstrate that the microclimatic outcomes of specific spatial interventions provide consistent results that are reusable and verifiable within the same urban and climatic context (Amman's neighborhoods), these results function as prescriptive guidance for evidence-based design and investments.

This thesis mainly focuses on the ability to create prescriptive guidance and evidence-based interventions that are verified and reusable throughout adjacent neighborhoods is derived from repeated ENVI-met experiments conducted in subchapter 4.2.1, showcasing adjacent neighborhoods in Amman under comparable and near exact morphological and climatic conditions. Throughout 40 comparable simulations, interventions such as asphalt reduction, courtyard typologies, and green space insertion produced nearly identical temperature reductions across sites, confirming that outcomes were not incidental.

While the research does not claim universal transferability across climates, it demonstrates that within a defined urban and climatic context, simulation results can be reproduced and used predictively.

Since Urban Metabolism aids in identifying spatial hotspots and translating diagnosis into targeted intervention, this finding shifts microclimatic simulation from a descriptive or exploratory tool into a prescriptive planning instrument. Within the Amman context, ENVI-met simulations can support locally grounded design guidance, enabling planners to link specific spatial configurations to predictable metabolic outcomes. In this way, microclimatic modeling directly contributes to improving metabolic flows, particularly climate, energy demand, and human comfort, through evidence-based decisions.

Beyond intervention predictability, the simulations also reveal the presence of latent metabolic reserves within dense urban environments. As demonstrated in higher-performing neighborhoods in Amman and in the institutional garden case of the Budafok Cemetery, underutilized spaces such as courtyards, vacant plots, and institutional landscapes possess significant untapped cooling potential. When strategically activated through targeted GI interventions, these spaces can measurably enhance local microclimate performance, reinforcing the role of micro-scale spatial adjustments in recalibrating broader urban metabolic conditions.

6.5 Thesis 5: According to my simulation results, strategic approach targeting high impact areas based on evidence provides optimal urban intervention. For example: asphalt mitigation outperforms a blanket policy, where the first removal has huge thermal benefits, and further reduction produces smaller gains.

This thesis is extremely important for sequencing urban interventions within constrained planning and resource contexts like Amman, in which gaining the best metabolic benefit for the least amount invested in resource constrained cities is essential.

This thesis is derived from a series of ENVI-met simulations presented in Section 4.2.1 where several asphalt-reduction scenarios were tested in Amman, Jordan across six intervention scenarios per neighborhood (totaling 12 simulations) within 150x150 blocks,

By establishing the concept of the 'Diminishing Returns Threshold' for asphalt mitigation, a key principle where multiple asphalt-reduction scenarios were tested in Amman. The results consistently showed that the first approximately 8% reduction of asphalt coverage produced the largest decrease in near-surface air temperature, the finding emphasizes on the intervention and not the quantitative percentage (The number is specific for the context and will vary in another geographical contexts), while further reductions resulted in progressively smaller thermal gains which had a lower value. This confirms that urban microclimatic response is not linear and that intervention alone does not guarantee proportional benefit.

Rather than advocating for extensive or indiscriminate asphalt removal, the findings emphasize the importance of strategic, phased interventions focused on thermally critical surfaces such as parking areas, wide traffic corridors, and exposed intersections. Within the arid context of Amman, this approach allows municipalities to prioritize locations where limited investments can achieve the greatest metabolic effect, particularly in reducing heat stress and cooling demand. In contrast, interventions involving courtyard buildings or conversion of empty lots into green zones displayed near-linear benefits, with each incremental increase in green surface translating into measurable improvements in neighborhood-scale microclimate. This finding also highlights that intervention type matters: while some strategies (green lots, courtyards) can be scaled proportionally, asphalt mitigation requires careful, strategic planning to maximize impact.

In summary, this research provides an evidence-based framework for tactical urbanism, demonstrating that the effectiveness of microclimatic interventions depends not only on the type of strategy but also on the scale and sequence of implementation. By quantifying the Diminishing Returns Threshold for asphalt and contrasting it with linear responses in other interventions, this thesis offers practical guidance for strategic, flow-oriented urban planning, enhancing the metabolic performance of neighborhoods while ensuring efficient use of resources.

6.6 Thesis 6: Green Infrastructure functions as a crossflow mediator within urban metabolism, and its spatial distribution reveals how metabolic benefits and burdens are allocated (equity) especially in scarce cities, connecting the overlapping relation of GI, UM and spatial justice as an internal dimension of metabolic performance.

This thesis is derived from the integrated results presented across Chapters 4.1, 4.2, 4.3, and 4.4, where GI was consistently used as an element through which multiple urban metabolic flows intersect and become spatially legible. Rather than functioning as a single environmental layer, GI simultaneously influenced microclimate regulation, surface temperature, water behavior, pedestrian comfort, and biotic performance.

This multi-scalar influence positions GI as a mediating structure between otherwise separate metabolic flows. The relationship or synthesis between GI and UM can also be seen in the neighborhood-level metabolic diagnosis in Amman (Chapter 4.3) which demonstrates that variations in GI quality and continuity correspond directly with differences in climate exposure, walkability, and overall metabolic performance.

Crucially, the spatial distribution of GI revealed clear patterns of metabolic equity and inequity in Amman. High-performing metabolic conditions were not evenly distributed across the city but were concentrated in neighborhoods with higher land value and favorable planning regulations. This finding confirms that equity does not operate outside the metabolic system, rather, it is expressed through how metabolic benefits and burdens are spatially allocated. GI thus functions as both a diagnostic indicator, revealing where metabolic stress accumulates, and a corrective instrument through which flows can be recalibrated.

While the distribution of GI might not be the same in all cities, its distribution nevertheless gives an indication of spatial injustice, and in that spatial justice is a crucial part of the regulating framework and implications of UM flows, where GI is only a small part of, the distribution of different UM flows like energy, water, and other flows when assessed can provide an essential indicator of spatial justice in a city, and in the case of Amman, an arid city with scarce greenery, GI shines as a UM flow for this exact specific case, indicating inequity.

6.7 Thesis 7: Tree species within Green Infrastructure function as differentiated metabolic agents, whose selection influences the efficiency and side effects of urban metabolic flows, particularly in

arid and resource-constrained urban contexts. (cooling performance, water demand, air quality, carbon, and long-term resilience)

This thesis builds on microclimatic simulations and thesis 6 position on GI and UM, conducted within the dissertation, and explained in chapter 4.3.2. Rather than treating urban trees as a homogeneous green layer, the research demonstrates that different species exhibit distinct metabolic behaviors, producing varied impacts on cooling, evapotranspiration, water consumption, and air-quality-related flows.

The contribution does not claim universal novelty in recognizing species differences, because this is well established in ecological and forestry literature. Its contribution lies instead in operationalizing species choice within an UM framework, linking tree selection directly to measurable metabolic outcomes and urban design decisions. In arid contexts such as Amman, where water scarcity and heat stress intensify trade-offs, inappropriate species selection can make metabolic burdens worse.

By framing species selection as a matter of metabolic performance instead of aesthetics or survivability or even shade. This thesis supports evidence-based GI planning in the science of UM which is not discussed often. It complements the broader GI–UM–equity framework by showing that not only the distribution of GI matters, but also its internal composition, reinforcing the need for context-sensitive, flow-aware landscape decisions.

6.8 Thesis 8: In the context of Amman, governance frameworks and building regulations condition the spatial potential of some metabolic flows (like biota, climate and air quality), shaping environmental performance and spatial inequality. These practices systematically influence Green Infrastructure distribution, thermal exposure and thus the metabolic balance.

This thesis is derived from the combined analysis of zoning regulations, neighborhood morphology, and metabolic performance outcomes presented in Chapters 4.3 and 4.4. The findings show that governance mechanisms, such as zoning classes, density limits, setback requirements, and surface allocation play an important role in determining metabolic flows performance.

In Amman, lower density zones with larger setbacks and higher proportions of unbuilt land structurally allow for greater GI integration, improved thermal regulation, and enhanced pedestrian comfort. This does not mean all urban metabolic flows are better, in fact the complexity of urban systems might mean better waste management in denser zones, which have because of the zoning codes limited open-space requirements with less impervious surfaces, restricted vegetation, and heat exposure. From these regulations the contrasts are born, reflecting regulatory conditions embedded in the planning system of Amman.

The research does not claim that governance alone determines metabolic performance, nor that these findings are universally transferable. Rather, it demonstrates that within Amman's climatic, socio-economic, and regulatory context, planning frameworks act as a conditioning layer that amplifies the effectiveness of GI and other metabolic interventions. Governance therefore functions as an indirect but influential determinant of how environmental benefits and burdens are distributed across neighborhoods. By empirically linking regulatory structures to measurable differences in microclimate, GI distribution, and lived environmental conditions, this thesis positions planning policy as an internal component of urban metabolic performance rather than an external administrative factor.

5. CONCLUSIONS AND RECOMMENDATIONS

This dissertation sets out to examine how UM can be spatialized and operationalized through its relation to GI to better understand environmental performance, lived urban conditions, and spatial inequality. Responding to conclusions and some scholars critique of Urban Metabolism as overly aggregated and technically focused, the research tested a multi-scaled diagnostic tool that integrates street-level observation, neighborhood-scale metabolic assessment, microclimatic simulation, and spatial equity analysis.

A key contribution of the work lies in positioning GI as a crossflow analytical lens within UM, rather than as a standalone environmental asset. particularly in arid, resource-constrained contexts like Amman.

The tools, combining street-level audits, microclimatic simulation, neighborhood-scale assessment, and policy analysis, provided results that are effective in revealing how metabolic flows (energy, water, climate, people, materials) are distributed in relation to different proposed scenarios, and district conditions, but also unevenly distributed they are.

1. An important outcome of the dissertation is the demonstration that Urban Metabolism cannot be fully understood without attention in the beginning to spatial scale and configuration. While city scale analysis remains essential and original for understanding inputs and outputs, they tend to obscure localized variation in exposure, and comfort masked by total numbers. By shifting the analytical focus toward streets and neighborhoods, the research reveals how metabolic processes are experienced unevenly across space, and how urban form, surface materials, and GI shape these conditions in everyday life.

Methodologically, the dissertation advances Urban Metabolism by demonstrating the value of human- or neighborhood-scale diagnostic tools and by analyzing the relation of UM-GI-Equity.

2. The tools used, Street-scale metabolic profiling using pedestrian-level imagery made it possible to capture vertical greenery,

enclosure, surface composition, and perceptual exposure that are systematically missed by top-down datasets, an element that works as real-time sensor for data in ratios to create dynamic, feedback-oriented urban management systems.

3. High-resolution microclimatic simulation further contributed by operationalizing climate as a diagnosable and design-responsive metabolic flow at the neighborhood scale. Rather than treating climate as a passive background condition, it showed how spatial configuration and GI interventions recalibrate UM flows. This showcased how to Adopt a strategic, phased intervention approach for GI investment, to Prioritize high-impact, low-cost actions first, such as targeted asphalt removal in key heat corridors and the activation of latent green reserves. It also provides detailed changes from small tree species change or building typologies and gave the opportunity for evidence-based scenario testing of GI designs or even testing tree species as metabolic agents.

4. The results showcased that in Amman, the stark east-west divide in environmental quality is not incidental but is metabolically and systematically structured by urban form, zoning regulations and land value dynamics, which was shown through the analysis of different regulations, building codes and GI distribution. High-performing metabolic conditions were not evenly distributed across the city but were concentrated in neighborhoods with higher land value and favorable planning regulations. This finding confirms that equity does not operate outside the metabolic system, rather, it is expressed through allocation. GI thus functions as both a diagnostic indicator and corrective instrument/flow.

5. In the arid context of Amman, where GI is scarce and climatic stress is high, its presence or absence becomes a particularly strong indicator of localized metabolic performance. Where GI is fragmented or inaccessible, metabolic pressures such as heat stress, reliance on artificial cooling, and environmental discomfort accumulate disproportionately. This finding indicates that

questions of spatial equity are embedded within urban metabolic processes, as they reflect how environmental benefits and burdens are unevenly distributed across urban space. In summary spatial equity emerges from the spatial organization of metabolic flows.

6. Taken together, the findings reinforce a core conclusion of the dissertation: UM, GI, and spatial equity are not separate analytical domains, but overlapping dimensions of the same urban system. Urban Metabolism provides the framework for understanding flows, GI acts as a spatial mediator with flows, even part of biota as a flow, and equity describes how the benefits and burdens of these flows are distributed across neighborhoods. This relationship is especially visible on the neighborhood scale, where differences in form, regulation, and access translate directly into everyday environmental experience. Each element can spot malfunctions in another in different ways or scales, evident more in certain cities.

7. The dissertation does not claim universal metrics or predictive models applicable across all cities, nor does it present GI as the only regulator of UM. Instead, it contributes a transferable methodological logic: a way of combining existing tools (traditional UM tools) with street-level observation, microclimatic simulation, neighborhood-scale metabolic assessment, and spatial analysis, to diagnose urban conditions in a manner that is spatially explicit, human-centered, and sensitive to local context. In this sense, the work positions UM not as a closed technical system, but as a flexible analytical framework capable of informing more nuanced, equitable or just, and context-aware urban planning.

The dissertation provides both conceptual clarification and practical insight into how cities like Amman, facing climatic stress and resource constraints, can better align environmental performance with lived urban conditions in addition to better understanding into the complex relation of UM flows.

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