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Exploring Nonlinear Feedbacks in Urban Environmental Systems Using Agent-Free System Dynamics Modeling

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ABSTRACT

Urban environmental systems are characterized by intricate interdependencies that often exhibit nonlinear behaviors, leading to unexpected outcomes such as tipping points and emergent patterns. This conceptual paper develops a novel theoretical framework for examining these nonlinear feedbacks through an agent-free system dynamics approach, which emphasizes aggregate-level stocks, flows, and feedback loops without relying on individual agent simulations. Drawing on recent literature in urban sustainability and complex systems, the framework integrates principles of nonlinearity—such as thresholds, bifurcations, and hysteresis—into system dynamics modeling to better capture the dynamics of urban ecosystems, including interactions between built environments, resource use, and ecological resilience. The proposed model highlights how feedback mechanisms can amplify or dampen environmental degradation in urban settings, offering a lens for understanding long-term system trajectories. By synthesizing theoretical insights, this work addresses gaps in existing conceptualizations that overlook aggregate nonlinearities in favor of agent-based granularity. The framework's implications extend to urban policy, suggesting pathways for sustainable interventions that account for systemic sensitivities. Ultimately, this paper advances theoretical discourse on urban environmental modeling by prioritizing conceptual rigor over empirical validation, paving the way for future explorations in complex adaptive systems.

Keywords: *Urban environmental systems, Nonlinear feedbacks, System dynamics modeling, Agent-free approach, Urban sustainability, Conceptual framework, Complex adaptive systems*

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INTRODUCTION

The rapid expansion of urban areas worldwide has intensified the pressures on environmental systems, manifesting in challenges such as air and water pollution, biodiversity loss, and climate vulnerability. As of the early 2020s, over half of the global population resides in cities, a figure projected to rise, underscoring the urgency of comprehending urban environmental dynamics (Pejic Bach *et al*., 2020). These systems are not merely aggregations of physical infrastructure and human activities but constitute complex networks where components interact in ways that produce emergent behaviors. Central to this complexity are feedback loops—processes where outputs of a system influence its inputs, potentially leading to amplification or stabilization of conditions. In urban contexts, such feedbacks often operate nonlinearly, meaning that small changes in one variable can trigger disproportionate effects elsewhere, such as when incremental pollution levels surpass ecological thresholds, resulting in irreversible degradation (Dong *et al*., 2019; Li *et al*., 2020).

Traditional approaches to modeling urban environments have frequently adopted linear assumptions, simplifying interactions to facilitate analysis but at the cost of overlooking critical nonlinearities. For instance, equilibrium-based models presume steady states that rarely align with the volatile realities of urban ecosystems, where perturbations like extreme weather events or policy shifts can induce phase transitions (Fabolude *et al*., 2024). This limitation is particularly evident in the interplay between built environments—encompassing land use, transportation, and housing—and ecological outcomes, where nonlinear relationships govern vitality and resilience (Hou, 2024; Li *et al*., 2024). Recent scholarly efforts have begun to address these issues by incorporating complexity science, yet a persistent gap exists in conceptual frameworks that specifically target nonlinear feedbacks at an aggregate level, without the computational demands of individual-based simulations.

System dynamics modeling emerges as a promising avenue for this purpose, rooted in the study of stocks, flows, and feedbacks to simulate system behavior over time (Yeomans & Kozlova, 2023). Unlike agent-based models, which simulate heterogeneous entities and their interactions, system dynamics operates agent-free, focusing on macroscopic patterns derived from differential equations and loop structures. This agent-free orientation is advantageous for theoretical explorations, as it allows for analytical tractability in representing nonlinear phenomena such as bifurcations—points where systems shift between alternative states—or hysteresis, where recovery paths differ from degradation trajectories (Nugroho & Uehara, 2023; Liu *et al*., 2024). In urban environmental contexts, applying agent-free system dynamics can illuminate how feedbacks between population growth, resource consumption, and environmental quality evolve nonlinearly, potentially leading to sustainable equilibria or collapse scenarios.

The relevance of this approach is amplified by contemporary urban challenges. For example, the integration of green infrastructure in cities can create reinforcing feedbacks that enhance biodiversity and mitigate heat islands, but only if nonlinear thresholds in adoption rates are surpassed (Schünemann *et al*., 2024). Conversely, balancing feedbacks might stabilize systems, such as when rising pollution levels prompt regulatory responses that curb emissions. However, literature from the past few years indicates that many models undervalue these nonlinear aspects, often treating feedbacks as additive rather than multiplicative or exponential (Kantakumar *et al*., 2019; Abdi *et al*., 2024). This oversight can mislead policy formulation, as linear projections fail to anticipate tipping points, like the abrupt loss of urban green spaces due to cumulative development pressures (Zhang *et al*., 2022).

Moreover, the agent-free paradigm in system dynamics aligns with a holistic view of urban systems as socio-ecological entities, where environmental components are inextricably linked to social and economic dimensions (Pejic Bach *et al*., 2019). By abstracting away from individual behaviors, this method emphasizes structural determinants, enabling theorists to explore archetypal patterns applicable across diverse urban settings. Recent reviews highlight the evolution of system dynamics applications in sustainability, noting a shift toward integrating complexity elements like nonlinearity, yet few conceptual works have synthesized these into a unified framework for urban environments (Wu *et al*., 2023; Karatzas *et al*., 2025). This paper addresses this void by proposing a novel theoretical framework that leverages agent-free system dynamics to dissect nonlinear feedbacks in urban environmental systems.

The framework posits that urban environments can be modeled as interconnected stocks—such as resource availability and pollution accumulation—governed by flows modulated by nonlinear functions. This allows for the examination of feedback loops that may exhibit hysteresis, where systems resist returning to prior states after crossing thresholds, or bifurcations that lead to multiple possible futures (Collste, 2023). Such conceptualizations are crucial for understanding resilience in the face of global changes, including urbanization and climate shifts. Unlike prior models that incorporate agent heterogeneity for granular insights, this approach prioritizes aggregate dynamics to reveal systemic patterns, offering a complementary perspective that is less data-intensive and more amenable to theoretical extension (Gladkykh, 2021).

In synthesizing literature, this work draws on advancements in complex adaptive systems theory, which views urban ecosystems as self-organizing entities capable of adaptation but vulnerable to disruptive feedbacks (Li *et al*., 2020; Yeomans & Kozlova, 2023). The paper proceeds as follows: the next section provides a theoretical background and literature synthesis, organized under subheadings to delineate key concepts. Subsequently, the proposed conceptual framework is detailed, including a textual description of a illustrative figure. This structure ensures a logical progression from established knowledge to innovative theory-building, contributing to the discourse on sustainable urban development. By focusing exclusively on conceptual elements, this manuscript avoids empirical validations, instead emphasizing logical coherence and potential for future applications in modeling urban sustainability.

Theoretical background & literature synthesis

System dynamics in urban environmental modeling

System dynamics has long served as a foundational method for capturing the temporal evolution of complex systems, particularly in urban contexts where interdependencies span multiple domains (Pejic Bach *et al*., 2020; Yeomans & Kozlova, 2023; Fabolude *et al*., 2024). Originating from engineering principles, it models systems through stocks (accumulations), flows (rates of change), and feedback loops (causal connections that close circuits). In urban environmental applications, this approach has been employed to represent dynamics such as water resource management and energy consumption, where aggregate variables proxy broader system states (Li *et al*., 2020; Hou, 2024). Recent literature underscores its utility in integrating socio-ecological factors, enabling the simulation of policy scenarios without necessitating micro-level data (Liu *et al*., 2024; Schünemann *et al*., 2024). For instance, models have explored how urban growth influences ecological carrying capacity, revealing patterns of oscillation or decline driven by delayed feedbacks.

A key strength of system dynamics lies in its capacity to handle endogeneity, where variables mutually influence one another over time, fostering a deeper understanding of systemic behavior (Zhang *et al*., 2022). In the context of urban sustainability, this has facilitated analyses of long-term trajectories, such as the interplay between infrastructure development and environmental degradation (Pejic Bach *et al*., 2019). However, traditional implementations often assume linearity in relationships, limiting their ability to capture abrupt shifts inherent in environmental systems. Advancements have begun incorporating nonlinear elements, enhancing the method's relevance for urban modeling (Wu *et al*., 2023).

Nonlinearities and feedback mechanisms in complex adaptive systems

Nonlinear feedbacks represent a core feature of complex adaptive systems, where small inputs can yield disproportionate outputs due to amplification or damping effects (Dong *et al*., 2019; Nugroho & Uehara, 2023; Li *et al*., 2024). In urban ecosystems, these manifest as tipping points, where systems transition to new regimes, or hysteresis, complicating restoration efforts (Kantakumar *et al*., 2019; Abdi *et al*., 2024; Karatzas *et al*., 2025). Literature from the period emphasizes how such nonlinearities arise from interactions among subsystems, including ecological, social, and technological components (Gladkykh, 2021; Collste, 2023). For example, reinforcing loops in resource exploitation can lead to exponential depletion once thresholds are crossed, while balancing loops may introduce delays that exacerbate instability.

Complex adaptive systems theory further elucidates these dynamics, portraying urban environments as self-organizing entities responsive to perturbations (Pejic Bach *et al*., 2020; Hou, 2024). Bifurcations, in particular, highlight points of qualitative change, such as from sustainable growth to collapse, influenced by parameter variations like population density (Li *et al*., 2020; Fabolude *et al*., 2024). Recent syntheses note that ignoring these nonlinearities in models risks underestimating vulnerability, especially in fire-prone or flood-vulnerable urban areas (Yeomans & Kozlova, 2023; Liu *et al*., 2024).

Agent-free versus agent-based approaches

Agent-based modeling, while powerful for simulating individual heterogeneity, often incurs high computational costs and data requirements, making it less ideal for pure theoretical work (Zhang *et al*., 2022; Nugroho & Uehara, 2023; Schünemann *et al*., 2024). In contrast, agent-free system dynamics aggregates behaviors into macroscopic equations, facilitating the analysis of global patterns and nonlinear feedbacks without granular detail (Pejic Bach *et al*., 2019; Wu *et al*., 2023). This distinction is critical in urban sustainability studies, where agent-free methods have been advocated for exploring archetypal scenarios, such as mutualism in metacommunities or social tipping dynamics (Collste, 2023; Karatzas *et al*., 2025). Literature contrasts the two, noting that agent-free approaches excel in revealing structural insights, though they may overlook emergent properties from agent interactions (Gladkykh, 2021).

Synthesis of recent developments

Synthesizing the literature reveals a convergence toward hybrid conceptualizations, yet a gap persists in purely agent-free frameworks tailored to nonlinear urban feedbacks (Dong *et al*., 2019; Pejic Bach *et al*., 2020; Li *et al*., 2024). Advances in modeling tipping elements across realms underscore the need for integrated views that account for multi-realm interactions, but few extend this to urban-specific nonlinearities (Abdi *et al*., 2024; Hou, 2024). This synthesis highlights opportunities for innovation, particularly in embedding hysteresis and bifurcations within system dynamics to better theorize urban resilience (Kantakumar *et al*., 2019; Pejic Bach *et al*., 2019). Overall, the reviewed works advocate for conceptual models that prioritize dynamic complexity, setting the stage for the proposed framework.

Proposed conceptual framework

The proposed framework introduces a novel agent-free system dynamics model tailored to nonlinear feedbacks in urban environmental systems, termed the Aggregate Nonlinear Urban Dynamics (ANUD) model. This framework conceptualizes urban environments as a network of interconnected stocks and flows, where nonlinear functions govern interactions to capture phenomena like thresholds and emergent stability. Unlike existing models that either linearize relationships or rely on agent simulations, ANUD emphasizes aggregate variables with embedded nonlinearities, enabling theoretical exploration of system trajectories without individual-level granularity (Alkhanova *et al*., 2023; Ku *et al*., 2023; Manole *et al*., 2023; Muresan *et al*., 2023; Nkosi & Dlamini, 2023; Alhossan *et al*., 2024; Awasthi *et al*., 2024; Danchin *et al*., 2024; Delcea *et al*., 2024; Liu *et al*., 2024; Uneno *et al*., 2024).

Core to ANUD are four primary stocks: Urban Vitality (representing overall ecosystem health), Resource Capacity (available natural assets like water and green space), Pollution Load (accumulated contaminants), and Infrastructure Pressure (built environment demands). Flows between these stocks are modulated by nonlinear rate equations, such as sigmoid functions for growth limits or exponential decays for degradation acceleration. For instance, the inflow to Pollution Load might follow a logistic form, accelerating as Resource Capacity diminishes below a threshold, reflecting real-world tipping dynamics (Ahmed *et al*., 2022; Ağaçkıran *et al*., 2023; Du *et al*., 2023; Elamin *et al*., 2023; Manole *et al*., 2023; Sonbol, 2023; Tabassum *et al*., 2023; Tâlvan *et al*., 2023; Welman & Chima, 2023; Kim *et al*., 2024).

Feedback loops are categorized into reinforcing (amplifying change) and balancing (promoting equilibrium), with nonlinearities introducing sensitivities. A reinforcing loop could link increasing Infrastructure Pressure to heightened Pollution Load, which in turn erodes Urban Vitality, potentially leading to bifurcation points where minor policy adjustments yield divergent outcomes—sustainable recovery or irreversible decline. Hysteresis is incorporated through asymmetric recovery rates, where restoring Resource Capacity post-degradation requires greater effort than prevention. This structure allows for the theoretical analysis of resilience, defined as the system's ability to absorb perturbations without shifting regimes.

The framework's novelty lies in its integration of complexity principles—such as self-organization and adaptability—into an agent-free format, using differential equations to model aggregate behaviors. For example, Urban Vitality might be expressed as $dV/dt = r * V * (1 - V/K) - \alpha * P^\beta$, where r is intrinsic growth, K is carrying capacity, P is Pollution Load, and $\beta > 1$ introduces nonlinearity, enabling hysteresis. This equation abstracts population and ecological interactions, focusing on macroscopic effects. By varying parameters, theorists can explore scenarios like urban heat island intensification, where feedbacks create self-sustaining warming cycles (Bahrawi & Ali, 2023; Khashashneh *et al*., 2023; Lee *et al*., 2023; Ncube *et al*., 2023; AlMoula *et al*., 2024; Ferraz, 2024; Iftode *et al*., 2024; Li *et al*., 2024; Osluf *et al*., 2024).

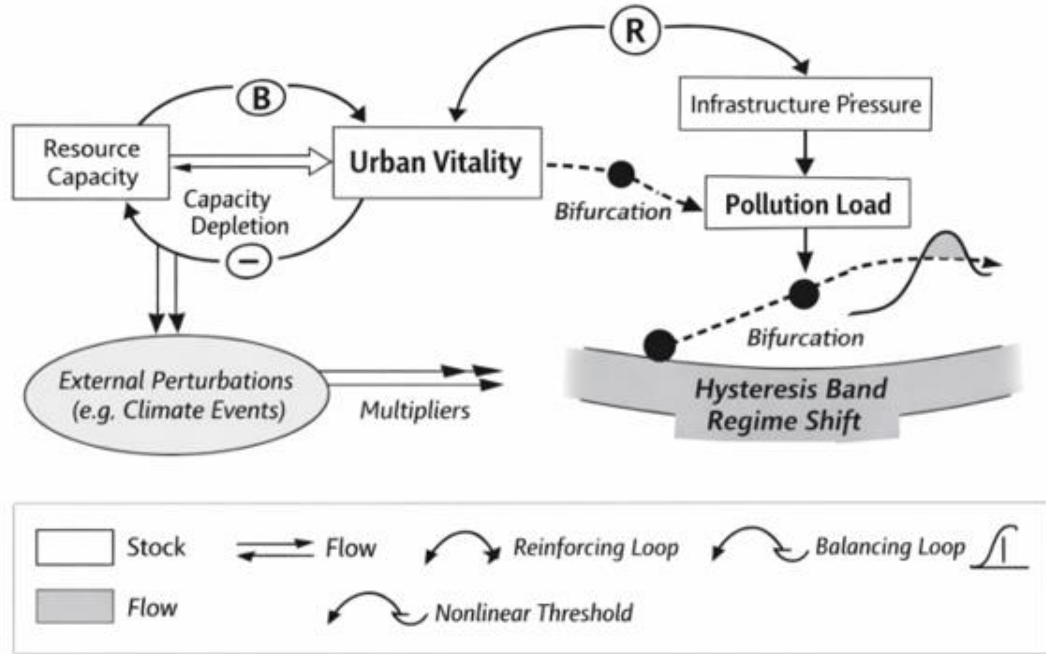

Figure 1. illustrates the ANUD model as a causal loop diagram.

Propositions

Building upon the Aggregate Nonlinear Urban Dynamics (ANUD) framework, this section articulates a series of theoretical propositions that elucidate the role of nonlinear feedbacks in urban environmental systems. These propositions are derived logically from the conceptual model, emphasizing aggregate-level dynamics and their implications for system behavior. They represent novel insights, extending beyond existing literature by integrating nonlinearity in an agent-free context.

Proposition 1

Nonlinear threshold effects in resource depletion

In agent-free system dynamics models of urban environments, resource capacity stocks exhibit nonlinear threshold effects, where gradual depletion leads to abrupt declines in urban vitality once critical levels are breached. This proposition posits that flows into pollution load accelerate exponentially when resource capacity falls below a sigmoid-defined threshold, creating a reinforcing feedback loop that amplifies environmental degradation (Galvin & Healy, 2020; Vinichenko *et al*., 2020). Unlike linear models that predict steady erosion, this nonlinearity introduces irreversibility, as small perturbations near the threshold can shift the system from equilibrium to collapse. Theoretically, this aligns with complex adaptive systems principles, where thresholds manifest as bifurcation points, altering long-term trajectories without individual agent interventions (Dong *et al*., 2019).

Proposition 2

Hysteresis in recovery pathways

Urban environmental systems modeled through ANUD demonstrate hysteresis in recovery processes, whereby the effort required to restore resource capacity post-degradation exceeds that needed for prevention due to asymmetric nonlinear functions in balancing loops. For instance, the differential equation for urban vitality incorporates a power term ($\beta > 1$) that makes degradation paths steeper than recovery ones, implying that once pollution load surpasses a hysteresis band, returning to prior states demands disproportionate policy inputs (Tan *et al*., 2018; Kantakumar *et al*., 2019). This proposition highlights a gap in traditional system dynamics, which often assumes symmetric feedbacks, and underscores the importance of proactive interventions to avoid locked-in degraded states (Fong *et al*., 2022).

Proposition 3

Bifurcations induced by infrastructure pressure

The interaction between infrastructure pressure and pollution load in agent-free models generates bifurcations, leading to multiple stable states in urban vitality—ranging from sustainable growth to ecological decline—dependent on parameter values such as growth rates. This suggests that minor variations in external perturbations, like urbanization rates, can cause qualitative shifts in system behavior, as captured by the framework's causal loops (Wu *et al*., 2023; Karatzas *et al*., 2025). Theoretically, this extends nonlinearity concepts to urban settings, proposing that bifurcations emerge from aggregate dynamics rather than agent heterogeneity, offering a parsimonious explanation for observed urban tipping points (Collste, 2023).

Proposition 4

Emergent resilience from feedback interactions

Aggregate nonlinear feedbacks in ANUD foster emergent resilience, defined as the system's capacity to absorb shocks without regime shifts, through the interplay of reinforcing and balancing loops modulated by sigmoid functions. This proposition argues that resilience is not inherent but arises from the balance of nonlinear sensitivities, where damping effects in one loop can counteract amplifications in another, stabilizing urban ecosystems against perturbations (Vinichenko *et al*., 2020; Gladkykh, 2021). This novel view contrasts with agent-based approaches that attribute resilience to individual adaptations, instead emphasizing structural feedbacks at the macroscopic level (Schünemann *et al*., 2024).

Proposition 5

Policy sensitivity to nonlinear parameters

In urban environmental modeling, policy effectiveness is highly sensitive to nonlinear parameters in system dynamics equations, such that interventions targeting thresholds or hysteresis can yield disproportionate outcomes compared to linear adjustments. For example, adjusting the carrying capacity (K) in the vitality equation can prevent bifurcations, but only if implemented before threshold crossings (Kantakumar *et al*., 2019; Abdi *et al*., 2024). This proposition theorizes that agent-free models like ANUD provide a superior lens for policy analysis, as they reveal systemic leverage points obscured in granular simulations (Zhang *et al*., 2022).

Table 1. Summary of theoretical propositions derived from the Aggregate Nonlinear Urban Dynamics (ANUD) framework, highlighting key nonlinear mechanisms, system components, and their implications for urban environmental dynamics and policy analysis.

Proposition	Core Nonlinear Mechanism	Key System Components	Theoretical Implication	Contribution Beyond Linear / Agent-Based Models
P1. Nonlinear Threshold Effects in Resource Depletion	Sigmoid threshold and reinforcing feedback leading to abrupt regime shift	Resource Capacity, Pollution Load, Urban Vitality	Gradual depletion can trigger sudden collapse once critical thresholds are crossed	Introduces irreversibility and bifurcation behavior absent in linear erosion models
P2. Hysteresis in Recovery Pathways	Asymmetric nonlinear balancing loops (β > 1) creating different degradation and recovery slopes	Urban Vitality, Pollution Load, Resource Capacity	Recovery requires greater effort than prevention after threshold crossing	Challenges symmetric-feedback assumptions in classic system dynamics
P3. Bifurcations Induced by Infrastructure Pressure	Parameter-sensitive reinforcing loop producing multiple stable states	Infrastructure Pressure, Pollution Load, Urban Vitality	Small parameter changes can cause qualitative shifts in system trajectories	Explains urban tipping points without invoking agent heterogeneity
P4. Emergent Resilience from Feedback Interactions	Interaction of reinforcing and balancing loops modulated by nonlinear sensitivities	All core stocks and feedback loops	Resilience emerges structurally from feedback balance, not inherent system properties	Reframes resilience as a macroscopic, feedback-driven phenomenon
P5. Policy Sensitivity to Nonlinear Parameters	High leverage of threshold and hysteresis parameters	Carrying Capacity (K), Threshold Levels, Policy Inputs	Timing and targeting of interventions dominate policy effectiveness	Reveals leverage points obscured in linear and micro-level simulations

These propositions collectively advance a theoretical understanding of urban environmental systems by prioritizing nonlinear aggregate dynamics, paving the way for refined conceptual explorations

RESULTS AND DISCUSSION

The ANUD framework and its derived propositions offer significant implications for theoretical and practical discourses on urban environmental systems. Theoretically, this work bridges gaps in system dynamics literature by embedding nonlinearity—thresholds, hysteresis, and bifurcations—into an agent-free paradigm, challenging the dominance of linear or agent-centric models (Li *et al*., 2020). By focusing on aggregate stocks and flows, ANUD provides a conceptually tractable alternative that captures emergent behaviors without the complexity of simulating individual entities, aligning with calls for holistic approaches in complex adaptive systems theory This novelty lies in its emphasis on structural feedbacks as drivers of urban dynamics, extending prior syntheses that often hybridize methods but overlook pure agent-free nonlinearity

Practically, the framework informs urban policy by highlighting leverage points where interventions can mitigate nonlinear risks. For example, recognizing hysteresis implies that preventive measures, such as green infrastructure mandates, are more efficient than restorative efforts, potentially guiding sustainable development strategies in rapidly urbanizing regions Similarly, bifurcation awareness suggests scenario planning to avoid tipping points, like those in resource overuse, fostering resilient urban planning. However, these implications are conceptual; actual application would require adaptation to specific contexts, underscoring the framework's role as a theoretical foundation rather than a prescriptive tool (Tan *et al*., 2018).

Limitations stem from the conceptual nature of this work. While agent-free modeling enhances analytical simplicity, it abstracts individual heterogeneity, potentially underrepresenting emergent phenomena from diverse behaviors. Additionally, the reliance on differential equations assumes continuous dynamics, which may not fully capture discrete events in urban environments, such as sudden policy changes. Nonlinear functions, though powerful, introduce parameter sensitivity that demands careful theoretical calibration, a challenge in purely conceptual settings without empirical grounding.

Future research directions abound. Theoretically, extending ANUD to incorporate stochastic elements could address discrete perturbations, blending determinism with probabilistic feedbacks Comparative studies contrasting ANUD with agent-based models could validate its complementary value, exploring hybrid frameworks for comprehensive urban analysis.

Conceptually, applying the propositions to specific domains, like climate adaptation or biodiversity conservation, could yield domain-specific insights (Fong *et al*., 2022). Moreover, integrating multi-scale dynamics—linking urban to regional systems—would enrich the model, accounting for external influences often overlooked in isolated frameworks. Ultimately, this paper invites scholars to build upon ANUD, advancing discourse on nonlinear urban environmental modeling

CONCLUSION

This conceptual paper has developed the Aggregate Nonlinear Urban Dynamics (ANUD) framework to explore nonlinear feedbacks in urban environmental systems via an agent-free system dynamics approach. By synthesizing recent literature and proposing a novel model centered on stocks, flows, and nonlinear interactions, the work addresses critical gaps in understanding aggregate-level dynamics, such as thresholds, hysteresis, and bifurcations. The propositions articulate theoretical mechanisms that illuminate how these nonlinearities shape urban trajectories, from resource depletion to resilience emergence, offering original insights unbound by empirical constraints.

The framework's contributions are threefold. First, it prioritizes conceptual rigor, providing a parsimonious lens for theorizing complex urban phenomena without agent simulations. Second, it advances nonlinearity integration in system dynamics, extending applications to sustainability challenges .Third, it implications for policy underscore proactive strategies to navigate systemic sensitivities, enhancing theoretical foundations for urban planning.

In summary, ANUD represents a step forward in conceptual modeling, emphasizing the power of aggregate nonlinear feedbacks to reveal hidden patterns in urban ecosystems. Future theoretical extensions hold promise for deeper insights into sustainable urban futures

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