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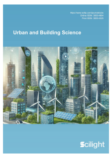

Review

Towards Dynamic Carbon Management: A Structured Analytical Review and Multi-Scale Framework for Urban Carbon Accounting

Akram A. N. Alabsi [1,*], Auwalu Faisal Koko [2], Khaled Mohammed Alshareem [3] and Ahmed Abdurabu Ali Al-Nehmi [3]

[1] College of Architecture and Urban Planning, Fujian University of Technology, Fuzhou 350118, China
[2] Department of Architecture, Faculty of Environmental Sciences, Baze University, Abuja 23401, Nigeria
[3] Department of Architecture, Faculty of Engineering, Thamar University, Thamar P.O. Box 87246, Yemen
* Correspondence: sallam_akram@hotmail.com or alabsiakram@fjut.edu.cn

How To Cite: Alabsi, A.A.N.; Koko, A.F.; Alshareem, K.M.; et al. Towards Dynamic Carbon Management: A Structured Analytical Review and Multi-Scale Framework for Urban Carbon Accounting. *Urban Build. Sci.* **2026**, *2*(3), 2. https://doi.org/10.53941/ubs.2026.100016

Received: 11 February 2026
Revised: 18 May 2026
Accepted: 4 June 2026
Published: 30 June 2026

Abstract: As cities increasingly become central arenas for achieving climate mitigation and carbon neutrality targets, the capacity to actively manage urban carbon rather than merely quantify emissions has emerged as a critical challenge for urban planning, design, and environmental governance. Despite substantial advances in quantifying urban emissions, existing studies frequently exhibit fragmented treatment of urban carbon processes, limited coupling across spatial scales, and insufficient integration of carbon storage and sequestration mechanisms, particularly those associated with nature-based solutions. These limitations constrain the capacity of urban planning and design to engage with carbon as a dynamic and spatially embedded urban system. This study aims to address these challenges through a structured analytical review of urban carbon research, employing an adapted PRISMA-informed protocol combined with process-oriented and scale-sensitive coding to systematically examine how carbon generation, accounting, storage, sequestration, and mitigation are conceptualised and operationalised in the literature. Comparative synthesis of the reviewed literature reveals persistent methodological and conceptual patterns, including the dominance of emission-centric accounting logics, the marginalisation of ecological and biogenic carbon processes, weak cross-scale integration between buildings and urban systems, and a prevailing reliance on static representations of carbon dynamics. Building on this analytical synthesis, the paper introduces Dynamic Carbon Management (DCM) as a conceptual framework that reframes urban carbon as an integrated, multi-process, and multi-scale system requiring coordinated management rather than isolated accounting. DCM framework formally links carbon flows across buildings, urban form, and nature-based interventions, providing an operational logic for understanding interactions between carbon generation, mitigation, storage, and sequestration over time. By shifting the analytical focus from static inventories toward dynamic management perspectives, this study contributes a theoretically grounded framework that advances urban carbon research and establishes a foundation for future empirical validation, modelling efforts, and policy-oriented applications aimed at supporting more adaptive, integrated, and multi-scale urban decarbonisation strategies.

Keywords: urban carbon management; dynamic carbon management (DCM); urban carbon accounting; multi-scale urban systems; carbon sequestration and storage; nature-based solutions

1. Introduction

Cities are at the core of global climate mitigation efforts [1], accounting for the majority of energy consumption and carbon emissions while simultaneously offering the greatest potential for decarbonization through spatial planning, building design, and systemic interventions [2–4]. In recent years, urban carbon neutrality has become a central policy objective, particularly in rapidly urbanizing regions such as China, where mitigation policies, sectoral transitions, and long-term neutrality pathways are actively pursued [5,6]. However, despite the proliferation of urban carbon targets and inventories, the effectiveness of current approaches remains constrained by conceptual and methodological limitations [7,8]. Recent critical reviews further indicate that urban GHG accounting frameworks remain constrained by inconsistencies in system boundaries, allocation procedures, and life-cycle integration, limiting the comparability and operational applicability of urban carbon assessments [9]. Much of the existing urban carbon research has focused on quantifying emissions, evaluating mitigation scenarios, or estimating the social cost of carbon under predefined pathways [8,10]. While such studies provide essential numerical baselines, they tend to conceptualize carbon as a static outcome rather than as a dynamic system embedded within urban form, infrastructure, and socio-ecological processes. As a result, carbon accounting has often been treated as an end in itself, rather than as a means to support integrated urban carbon management [11].

A growing body of recent studies highlights that current urban carbon frameworks remain fragmented along three key dimensions: process, scale, and intervention logic. First, carbon generation, accounting, mitigation, storage, and sequestration are frequently addressed in isolation, with limited analytical integration across these processes [9,12–15]. Second, studies often operate at single spatial scales most commonly the city or national level while neglecting the interactions between buildings, neighborhoods, and metropolitan systems [16,17]. Third, mitigation strategies remain heavily technology-oriented, prioritizing energy efficiency, electrification, and renewable energy deployment, while underrepresenting the role of ecological and nature-based processes [2,18,19]. Although nature-based solutions (NbS) are increasingly recognized for their co-benefits, their contribution to urban carbon dynamics is often framed as ancillary rather than structural [19,20]. In parallel, recent reviews on nature-based carbon management emphasize that ecological sequestration mechanisms and long-term carbon storage strategies remain insufficiently integrated into mainstream urban carbon governance frameworks [21]. This fragmentation limits the capacity of existing approaches to support coordinated, adaptive, and spatially differentiated decarbonization strategies. Similar concerns have recently been identified in urban building carbon-sink research, where fragmented treatment of material carbonation, ecological sequestration, and building-scale carbon storage continues to hinder the development of integrated urban carbon strategies [22].

Recent studies adopting systems perspectives have emphasized that urban carbon cannot be adequately understood through linear or static models alone [23]. Emerging urban metabolism studies increasingly advocate dynamic and life-cycle-based approaches capable of capturing interactions between resource consumption, embodied emissions, and socio-ecological transitions over time [14]. Interactions between the built environment, green infrastructure, and urban metabolism shape carbon flows over time and across spatial scales [24,25]. Moreover, empirical evidence from urban regeneration, industrial remediation, and neighborhood-scale interventions demonstrates that carbon reduction, sequestration, and co-benefits often emerge through integrated socio-technical and ecological processes rather than isolated measures [8,26]. Despite these insights, a coherent conceptual structure capable of linking multiple carbon processes dynamically across scales remains largely absent. Current approaches struggle to translate high-level carbon assessments into operational guidance for urban planning and design, particularly in contexts where mitigation policies interact, overlap, or even delay overall progress toward neutrality [10,27–29]. This gap points to the need for frameworks that move beyond static inventories toward adaptive and system-oriented carbon management. Based on the above analysis, a clear research gap emerges: while urban carbon accounting has matured in terms of methodological precision, it has not evolved into a comprehensive management paradigm capable of integrating multiple processes, spatial scales, and intervention types. Recent advances in dynamic scenario modelling, life-cycle simulation, and refined urban carbon monitoring further demonstrate the growing need for integrated frameworks capable of linking carbon flows, sinks, and mitigation pathways across multiple urban scales [30–32].

In particular, three limitations persist across the literature: (1) The dominance of emission-centric accounting logics over management-oriented frameworks. (2) Weak analytical coupling between building-, neighborhood-, and city-scale carbon processes. (3) The marginalization of carbon sequestration and storage, especially through nature-based solutions, within urban carbon strategies. To address these limitations, this study aims to synthesize existing urban carbon research through a structured analytical review and to develop a conceptual framework that reframes urban carbon as a dynamic, multi-process, and multi-scale system. Rather than proposing empirical solutions, the objective is to clarify relationships, expose structural gaps, and provide a coherent analytical foundation for future research and practice. This paper makes three main contributions. First, it provides a structured analytical synthesis of urban carbon literature, identifying dominant approaches, scale treatments, and conceptual blind spots. Second, it introduces Dynamic Carbon Management (DCM) as a theoretically grounded framework that integrates carbon generation, accounting, mitigation, storage, and sequestration within a unified management logic. Third, it offers a multi-scale operational perspective that links buildings, urban form, and nature-based interventions without prescribing context-specific solutions. This study contributes to the emerging debate on urban carbon governance by moving beyond static inventory-oriented approaches toward a more integrated and adaptive management perspective. And through providing a structured analytical synthesis of dominant urban carbon approaches, identifying conceptual fragmentation across scales and carbon processes, and proposing a multi-scale Dynamic Carbon Management framework linking accounting and management perspectives. The proposed DCM framework conceptually links carbon generation, mitigation, storage, and sequestration across multiple urban scales, while also providing a foundation for future operational, modelling, and policy-oriented applications in urban decarbonization planning.

2. Materials and Methods

2.1. Research Design and Review Strategy

This study adopts a structured analytical review design combined with conceptual framework development. The methodological approach is intentionally positioned between narrative reviews and full systematic reviews, drawing on PRISMA principles for transparency and rigor as illustrated in (Figure 1) that illustrates the structured identification and screening logic adopted to assemble the analytical literature corpus. The review focuses on urban carbon research addressing carbon generation, accounting, mitigation, storage, sequestration, and management within urban systems.

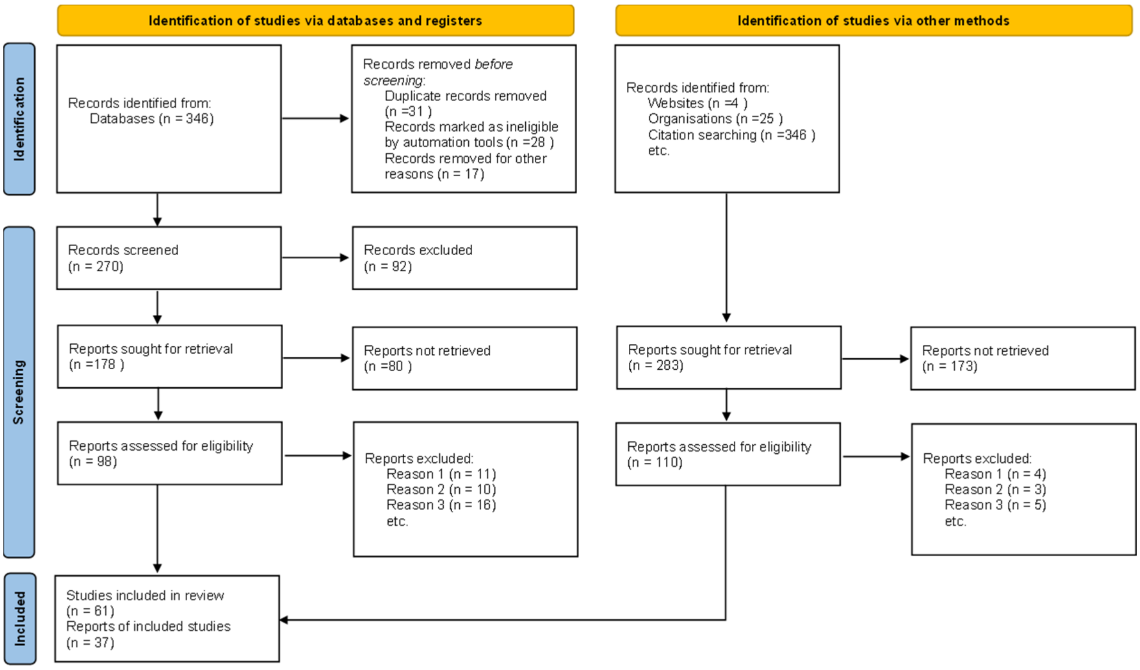

Figure 1. PRISMA-informed identification and screening process for the analytical literature corpus.

2.2. Literature Identification and Data Sources

The literature corpus was assembled through systematic searches across major academic databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, and thematically influential and recurrently referenced studies were identified during the screening process. Searches were conducted using combinations of the following keywords: Urban carbon accounting; carbon generation; carbon sequestration; carbon storage; urban carbon metabolism; carbon management; nature-based solutions; multi-scale urban systems.

The review covered studies published between 2004 and 2026, with particular emphasis on post-2015 studies reflecting post-Paris Agreement decarbonization agendas. Peer-reviewed journal articles constituted the core dataset, while selected authoritative reports and foundational works were included where they provided essential conceptual or methodological insights.

Inclusion, Exclusion, and Screening Logic: To ensure analytical consistency and relevance, studies were screened using explicit inclusion and exclusion criteria.

Inclusion criteria comprised:

- Explicit focus on urban or intra-urban carbon processes.
- Engagement with at least one of the following: emissions accounting, carbon flows, sequestration, storage, mitigation strategies, or management frameworks.
- Clear methodological articulation or conceptual contribution.

Exclusion criteria included:

- Studies limited to national-scale carbon inventories without urban disaggregation.
- Purely technical carbon capture or industrial process studies lacking urban relevance.
- Descriptive policy documents without analytical content.

The analytical content refers to studies that contain explicit conceptual, methodological, modelling, or evaluative components, rather than purely descriptive policy statements or non-analytical commentary. Following initial screening, a curated corpus of 37 core studies was retained for in-depth analysis. These studies formed the analytical backbone of the review and directly informed the subsequent synthesis and framework development.

2.3. Analytical Coding and Classification Framework

The retained studies were subjected to a multi-layered coding and classification process. Rather than relying on bibliometric clustering, the analysis employed conceptual and functional coding, enabling direct comparison across heterogeneous methodologies. The three analytical dimensions (Process, Spatial Scale, and Management Logic) were selected because they collectively capture the principal structural characteristics through which urban carbon studies conceptualize, operationalize, and manage carbon systems. The “Process” dimension reflects dominant carbon-process treatments (generation, mitigation, storage, and sequestration), the “Spatial Scale” dimension addresses the multi-scalar nature of urban carbon systems, and the “Management Logic” dimension captures the distinction between static accounting-oriented approaches and more adaptive or integrative management perspectives.

Each study was coded along three primary analytical dimensions:

1. Carbon Process Dimension: Carbon generation (emissions), Carbon accounting and reporting, Carbon mitigation strategies, Carbon storage, Carbon sequestration
2. Spatial Scale Dimension: Building scale, Neighborhood or district scale, City or metropolitan scale
3. Management Logic Dimension: Static accounting, Scenario-based assessment, System metabolism perspectives, Integrated or management-oriented approaches

This coding enabled the construction of comparative matrices (Processes × Scale, Constructs × Indicators), which served as the empirical basis for research findings.

Synthesis and Analytical Derivation of Results: The analytical synthesis proceeded in two stages. The first stage focused on descriptive classification and structured coding of the reviewed studies according to the predefined analytical dimensions. Which descriptive synthesis was used to identify dominant patterns, distributions, and emphases within the literature, forming the basis of the results presented in Section 3. Quantitative distributions (prevalence of accounting logics, scale focus) were derived directly from coded classifications rather than from secondary datasets. The second stage involved interpretive synthesis to identify recurring conceptual gaps, cross-scale inconsistencies, and underrepresented carbon processes, which subsequently informed the derivation of the DCM framework. An interpretive synthesis was conducted to identify structural gaps, conceptual misalignments, and underrepresented processes. This stage explicitly examined how different carbon processes and spatial scales were treated in isolation or combination, leading to the identification of persistent limitations. The coding structure was iteratively refined during an initial pilot screening stage to improve consistency and reduce interpretive ambiguity across the reviewed studies.

Extending the rapid coding to the full corpus confirms the structural patterns identified in the seed analysis. No additional constructs emerged beyond the six core processes (G, S, St, T, R, M). Across studies, carbon generation and transfer dominate analytical attention, while sequestration and storage remain operationally isolated. Crucially, dynamic management and explicit multi-scale coupling are consistently absent or only implicitly addressed, reinforcing the need for a formalized Dynamic Carbon Management framework.

2.4. Framework Construction Logic: From Review to DCM

Inductively, the Dynamic Carbon Management (DCM) framework emerged from the analysis of the synthesis. Framework construction followed a formal derivation logic:

1. Identification of recurring conceptual gaps and fragmentation patterns.
2. Abstraction of common functional elements across studies.
3. Reorganization of these elements into a coherent, multi-process and multi-scale structure.

DCM thus represents a theory-informed synthesis rather than a speculative model. It formalizes relationships already implied but rarely integrated within existing research, positioning carbon accounting as one component within a broader management-oriented system.

Methodological Scope and Limitations: Consistent with the aims of a structured analytical review, this methodology prioritizes conceptual clarity and analytical coherence over empirical generalization. While the framework is grounded in an extensive and systematically analyzed literature base, it does not claim empirical validation. This methodological positioning is intentional and aligns with the study’s objective to establish a foundational framework capable of guiding future empirical, modelling, and policy-oriented research. Despite efforts to improve analytical transparency, this study remains subject to several limitations inherent to structured analytical reviews, including potential interpretive subjectivity in qualitative coding, database selection constraints, and variations in methodological depth across the reviewed literature. In addition, the proposed DCM framework remains conceptually derived and requires future empirical validation and operational testing.

3. Results

3.1. Analytical Synthesis

Based on the structured analytical coding of the reviewed literature, an analytical matrix was developed to synthesize key carbon-related constructs, processes, indicators, and spatial scales. The need for a dynamic, multi-scale management framework is motivated by key gaps (static logic, scale disconnection, and limited integration), as illustrated in (Figure 2). This synthesis is summarized in Table 1 and provides the analytical basis for the results presented below.

Table 1. Analytical Matrix of Urban Carbon Constructs, Processes, Indicators, and Spatial Scales.

Construct	Core Indicators	Measurement Logic	Typical Data Source	Limitations in Literature
C1: Carbon Generation (G)	• Total CO_2e emissions • Sectoral emissions (buildings/transport/industry) • Per-capita emissions	Bottom-up/Top-down inventories	Energy statistics, fuel consumption, emission factors	Static snapshots; weak temporal dynamics; poor spatial resolution
C2: Carbon Sequestration (S)	• Annual sequestration rate (tCO_2e/yr) • Vegetation-based uptake • Soil carbon flux	Ecological models, NDVI-based estimation	Remote sensing, field surveys	Treated as isolated “benefit”; rarely coupled with emissions
C3: Carbon Storage (St)	• Carbon stock (tC) • Built environment stock • Biomass & soil storage	Stock accounting/accumulation models	Land use data, material inventories	Static stock view; no feedback to planning
C4: Carbon Transfers (T)	• Consumption-based emissions • Virtual carbon flows • Import/export embodied carbon	Input-Output/MRIO models	Trade statistics, IO tables	Abstract scale; disconnected from spatial planning
C5: Carbon Reduction (R)	• Avoided emissions • Efficiency gains (%) • Policy scenario deltas	Scenario modeling	Simulation models, policy scenarios	Scenario-dependent; lacks operational linkage
C6: Carbon Management (M)	• Control capacity • Feedback mechanisms • Multi-scale coordination	Rarely defined	—	**Major gap**: no formal indicators; no dynamic control logic

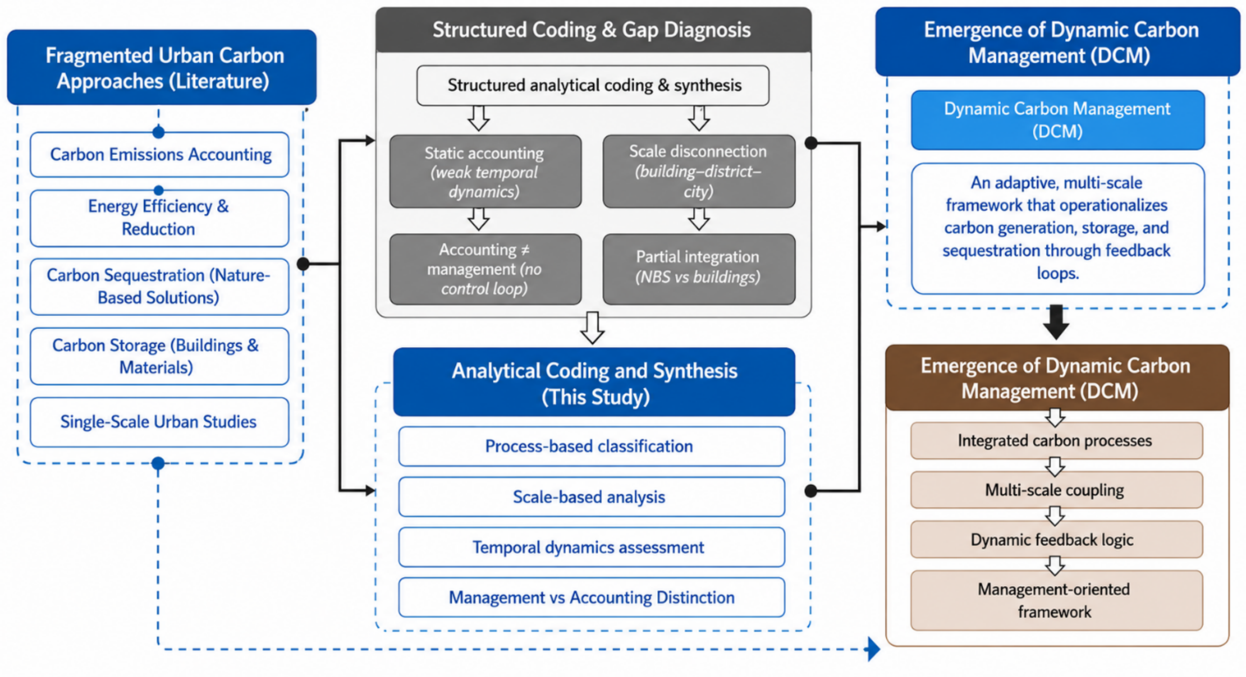

Figure 2. Analytical synthesis of fragmented urban carbon approaches and the emergence of Dynamic Carbon Management (DCM).

3.1.1. Distribution of Urban Carbon Approaches in the Literature

The structured review and rapid coding of the full literature corpus reveal a highly uneven distribution of urban carbon research approaches, both in terms of analytical focus and process coverage. As presented in Table 2 across the reviewed studies, approximately two-thirds of the literature concentrates primarily on carbon generation and emission accounting, typically through sectoral inventories, energy-based calculations, or consumption-oriented carbon footprints as illustrated in (Figure 3). This emission-centric orientation constitutes the dominant paradigm in current urban carbon research. [8,10,33,34].

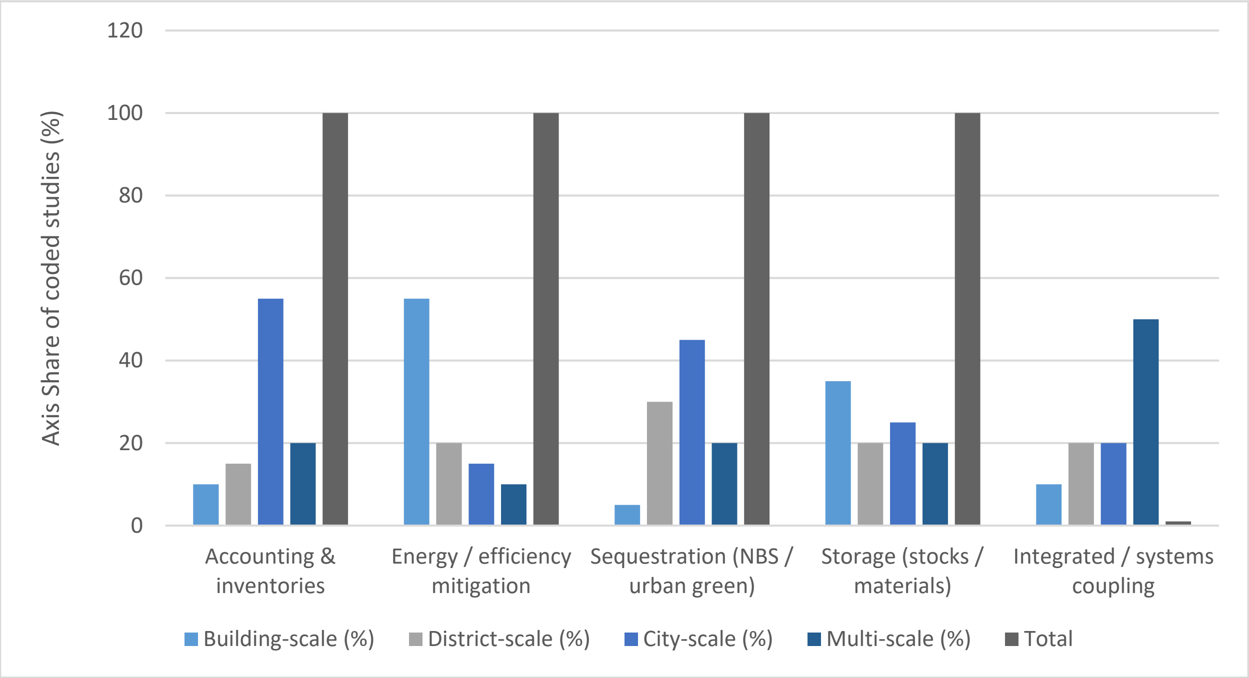

Figure 3. Distribution of dominant urban carbon research approaches (structured coding results).

Table 2. Distribution of Urban Carbon Research Approaches.

Approach Category	Primary Focus	Approx. Share of Literature (%)	Typical Methods
Emission-based accounting	Carbon generation (G)	~60–65%	Inventories, energy statistics
Transfer-based accounting	Embodied/virtual carbon (T)	~20–25%	IO, MRIO models
Sequestration & storage studies	S & St processes	~10–15%	Ecological models, GIS
Integrated approaches	Partial process integration	<10%	Hybrid/case-specific

A second cluster of studies representing roughly one-quarter of the reviewed corpus extends carbon accounting beyond territorial boundaries by incorporating carbon transfers and embodied emissions, most commonly through input–output analysis and virtual carbon flow modeling. While these approaches expand the conceptual scope of urban carbon accounting, they remain largely detached from spatially explicit urban systems and offer limited insights into operational decision-making at the building or neighborhood scale [1,11,35]. In contrast, studies addressing carbon sequestration and storage within urban environments account for a substantially smaller proportion of the literature, estimated at less than one-fifth of the reviewed works. These studies focus predominantly on urban green spaces, forests, soils, and, to a lesser extent, material stocks in the built environment [36–41]. Despite their relevance, sequestration and storage processes are typically analyzed in isolation, without explicit linkage to urban emission sources or broader carbon accounting frameworks.

Only a minor subset of studies attempts to integrate multiple carbon processes such as emissions, sequestration, and storage within a unified analytical structure. Even within this subset, integration remains partial and process-specific, with no consistent treatment of interactions across spatial scales or temporal dynamics [20,42,43]. Most notably, explicit treatment of carbon management as an operational, feedback-driven process is virtually absent across the reviewed literature, with management-related discussions largely confined to policy narratives or scenario descriptions rather than formalized analytical constructs [44–46]. Overall, the quantitative distribution of existing approaches highlights a pronounced imbalance in urban carbon research. Emission accounting and transfer-based analyses dominate the field, while integrative perspectives that address the dynamic coordination of carbon generation, sequestration, storage, and reduction remain marginal. This structural asymmetry provides a robust empirical basis for identifying the limitations of current approaches and motivates the need for more comprehensive and dynamically integrated frameworks, as examined in the subsequent sections.

3.1.2. Dominant Carbon Accounting Logics in Urban Studies

The analytical synthesis of the reviewed literature indicates that urban carbon research is shaped by a limited number of dominant accounting logics, each grounded in distinct methodological assumptions and analytical priorities. These logics differ not only in how carbon is quantified, but also in how urban systems are conceptually framed and operationalized. The most prevalent logic remains territorial, emission-based accounting, which focuses on quantifying carbon emissions occurring within administratively defined urban boundaries. This approach typically relies on energy consumption statistics, emission factors, and sectoral aggregation, and forms the methodological backbone of most city-level greenhouse gas inventories [47–50]. While this logic provides a standardized and policy-compatible basis for monitoring emissions, it largely treats cities as static emission sources, offering limited insight into underlying urban processes or cross-scale interactions (Table 3).

A second prominent logic is consumption-based and transfer-oriented accounting, which reallocates emissions along supply chains and attributes them to final urban consumption. Implemented primarily through input–output and multi-regional input–output (MRIO) models, this approach highlights the role of cities as drivers of global carbon flows rather than isolated emitters [44,51–53]. Although this logic expands the analytical boundary beyond city limits, it remains largely abstract, with weak spatial resolution and limited applicability to urban design, land-use planning, or localized mitigation strategies. A third, less dominant logic centers on biophysical carbon sequestration and storage, emphasizing the role of urban green spaces, forests, soils, and material stocks in capturing and retaining carbon [40,54–56]. These studies primarily adopt ecological or material-flow perspectives and provide valuable insights into carbon sinks within urban environments. However, sequestration and storage are typically assessed independently of emission sources, and are rarely integrated into broader urban carbon accounting frameworks.

Table 3. Dominant Carbon Accounting Logics and Their Characteristics.

Accounting Logic	Analytical Boundary	Key Strength	Key Limitation
Territorial emission-based	Administrative city	Policy compatibility	Static, emission-centric
Consumption-based/transfer	Global supply chains	Captures indirect emissions	Weak spatial relevance
Sequestration & storage-based	Local biophysical systems	Highlights urban sinks	Isolated from emissions
Hybrid approaches	Mixed	Broader perspective	Lack of integration logic

Across the reviewed literature, attempts to reconcile these accounting logics within a unified framework remain limited. Studies that combine multiple perspectives often do so in a parallel or additive ways, without establishing explicit relationships among emissions, sequestration, storage, and transfers [20,42,57]. As a result, existing accounting logics tend to coexist rather than interact, thereby reinforcing a fragmented understanding of urban carbon dynamics. Importantly, none of the dominant accounting logics explicitly frames carbon management as an active, feedback-driven process. Management considerations are typically embedded in policy recommendations or scenario analyses, rather than formalized as analytical components within the accounting frameworks themselves [50,58–60]. This absence of an explicit management logic limits the capacity of current approaches to support dynamic, multi-scale decision-making in rapidly evolving urban systems. In summary, the dominance of emission-centric, transfer-based, and sequestration-focused accounting logics each operating largely in isolation contributes to the analytical fragmentation identified in the reviewed literature. This fragmentation constrains the ability of existing approaches to capture the dynamic and interconnected nature of urban carbon processes, thereby motivating a critical reassessment of how urban carbon is conceptualized, analyzed, and ultimately managed. Across these dominant logics, three structural patterns consistently emerge:

- Process isolation: accounting logics address individual carbon processes independently.
- Boundary rigidity: analytical boundaries are rarely adaptable across scales.
- Lack of operationalization: accounting outcomes are weakly connected to planning and management actions.

3.1.3. Scale Treatment and Spatial Resolution in Urban Carbon Studies

The synthesis of the reviewed literature reveals that the treatment of spatial scale constitutes a critical yet persistently underdeveloped dimension of urban carbon research. Although cities are widely acknowledged as multi-layered systems composed of buildings, neighborhoods, and metropolitan regions, most carbon studies adopt single-scale analytical frameworks, with limited attention to cross-scale interactions or spatial differentiation. The city scale overwhelmingly dominates existing studies. A large proportion of the reviewed literature quantifies carbon emissions, footprints, or balances at the level of administratively defined cities, using aggregated indicators such as total emissions, sectoral contributions, or per-capita values [6,11,61,62]. While this scale aligns well with governance structures and policy reporting requirements, it often masks substantial intra-urban heterogeneity and limits the capacity to inform spatially targeted interventions as illustrated in Figure 4 and Table 4.

Studies operating at larger spatial extents, such as urban agglomerations or multi-city regions, further abstract urban carbon dynamics. These approaches typically rely on macro-scale datasets and input–output models to examine inter-city carbon transfers, regional emission patterns, or economic linkages [51,63,64]. Although valuable for understanding systemic carbon flows, such analyses offer minimal spatial resolution at the level where urban form, land use, and design decisions are made. In contrast, fine-scale analyses at the building or neighborhood level remain relatively scarce and fragmented. Where present, they are most commonly associated with studies of carbon sequestration, storage, or energy performance, focusing on urban vegetation, soils, or individual building stocks [7,35,53,59]. These studies provide detailed spatial insights but are rarely connected to city-wide accounting frameworks or higher-scale carbon assessments.

Notably, only a small subset of the reviewed literature explicitly addresses spatial coupling across scales. Even in these cases, scale transitions are typically handled through aggregation or disaggregation procedures rather than through explicit analytical relationships linking processes across spatial levels [44,45,57]. As a result, carbon processes occurring at different scales such as building-level energy use, neighborhood-level green infrastructure, and city-level carbon balances are treated as parallel phenomena rather than interdependent components of a unified system. The limited spatial resolution and weak cross-scale integration observed across the literature constrain the analytical and practical value of existing urban carbon approaches. Without explicit mechanisms to connect processes across spatial scales, current studies struggle to translate high-level carbon assessments into actionable strategies for urban planning, design, and management. This persistent gap in scale treatment reinforces the need for analytical frameworks capable of dynamically linking carbon processes across multiple spatial levels, a challenge that is further examined in the subsequent section [1,8,10,52].

Table 4. Scale Coverage in Urban Carbon Studies.

Spatial Scale	Typical Focus	Frequency in Literature	Main Limitation
Building	Energy, materials, sinks	Low	Poor city-level linkage
Neighborhood	Green infrastructure	Very low	Fragmented treatment
City	Emissions, inventories	High	Masks intra-urban variation
Agglomeration	Carbon flows	Medium	Abstract, non-spatial
Multi-scale	Explicit coupling	Rare	Conceptual only

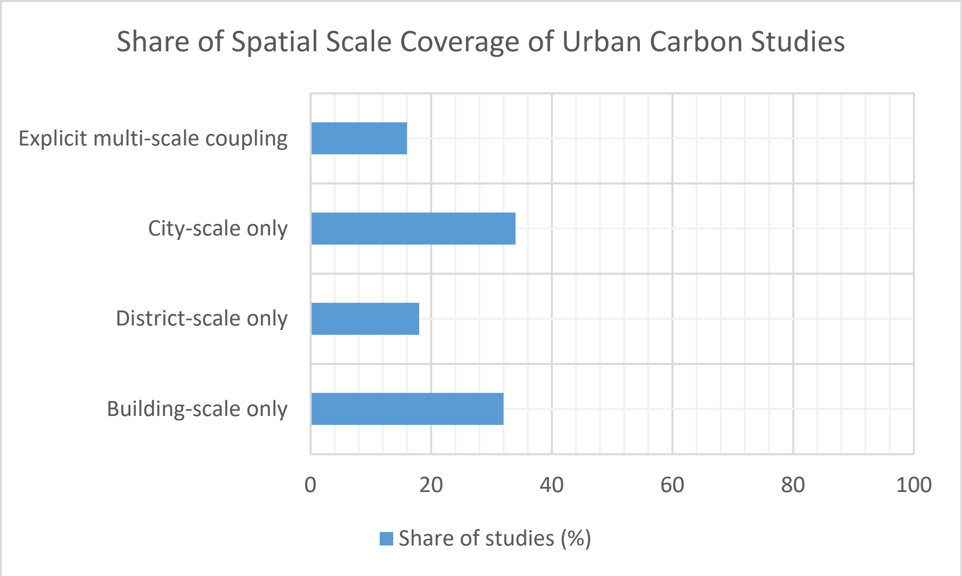

Figure 4. Dominance of single-scale approaches and limited multi-scale coupling in urban carbon studies.

3.2. Identified Gaps and Limitations in Existing Urban Carbon Approaches

Building on the analytical synthesis presented in the results, this section consolidates the systemic gaps and methodological limitations that recur across dominant urban carbon approaches. These limitations are not isolated shortcomings of individual studies, but rather reflect structural characteristics of the field that constrain the analytical and operational capacity of current urban carbon research.

3.2.1. Predominance of Static Accounting and Limited Temporal Dynamics

A central limitation across the reviewed literature is the predominant reliance on static accounting frameworks, as reflected in the dominant accounting logics and computational formulations summarized in Table 5. Most studies quantify urban carbon emissions, stocks, or balances at a single point in time or over coarse temporal intervals, offering limited insight into the dynamic evolution of carbon processes within rapidly changing urban systems. Temporal change is typically addressed through trend comparisons or scenario projections, rather than through explicit feedback mechanisms that link past states, current conditions, and future trajectories.

Table 5. Comparison of dominant urban carbon accounting logics, protocols, and computational formulations.

Accounting Logic/Typology	Typical Protocol/Method Family	Core Computational Formulation (Generic)	Primary Data Requirements	Strengths (What It Achieves)	Key Limitations (What It Misses)
Territorial GHG inventories	City-scale GHG inventories aligned with IPCC-style reporting; scope-based accounting (Scope 1–2, sometimes Scope 3)	$E = \sum(\mathrm{iA} \times \mathrm{iEF})$ $E = \sum_{s} \mathrm{sE}$ where: E = Total emissions iA = Activity for category i iEF = Emission factor for category i sE = Sectoral emissions total	Energy/fuel statistics, activity data, emission factors, administrative boundary definition	High traceability; easy comparability across cities; policy-friendly reporting	Often static (annual snapshot); limited dynamics; boundary bias; weak linkage to sequestration and storage; limited integration with urban form

Table 5. *Cont.*

Accounting Logic/Typology	Typical Protocol/Method Family	Core Computational Formulation (Generic)	Primary Data Requirements	Strengths (What It Achieves)	Key Limitations (What It Misses)
Production-based sector accounting	Sector-based territorial accounting; "where emissions are produced"	$I = \frac{E}{\text{GDP}}$ $\sum_s \text{sE} = E_{\text{prod}}$ where: E = Total emissions GDP = Gross Domestic Product I = Emissions intensity sE = Emissions from sector s ΣsE = Sum of all sectoral emissions	Sectoral energy data, industry statistics, fuel mix	Directly supports sector mitigation policies; clear responsibility attribution	Neglects cross-border embodied emissions; limited multi-scale coupling; weak representation of sinks
Consumption-based footprints	Carbon footprinting using Multi-Regional Input–Output (MRIO) or IO models; consumption responsibility	$\Delta S_t = S_q - E$ $E_{\text{consumption}} = y^T (I - A)^{-1} f$ where: ΔSt = Change in carbon stock at time t Sq = Carbon stock or sequestration quantity E = Emissions y^T = Transposed final-demand vector I = Identity matrix A = Technical coefficient matrix	IO tables, trade/interregional flows, consumption vectors, emission intensities	Captures carbon leakage and embodied emissions; aligns with supply-chain policies	Data intensive; assumptions and uncertainties high; limited spatial resolution; difficult operationalization for local planning
Urban metabolism/systems accounting	Urban carbon-energy metabolism models; stock-flow and sector coupling; sometimes hybrid physical + virtual flows	$\dot{S}_i = \sum_j F_{ji} - \sum_j F_{ij} - E_i$ where: $\dot{S}_i$ = Rate of change in stock for sector i F_{ji} = Inflow to sector i from sector j F_{ij} = Outflow from sector i to sector j E_i = Direct emissions from sector i	Multi-sector flow data, energy networks, material flows, sometimes GIS proxies	Integrates multiple subsystems; supports system-level thinking; closer to management logic	Still often lacks explicit control loop; coupling rules not standardized; model complexity limits transferability
Stock-based carbon & materials (built environment)	Material stock-flow analysis; building/infrastructure carbon storage; embodied carbon emphasis	$S_t = \sum_m (\text{mQ} \times \text{mCF})$ $S_t = S_{t-1} + \text{In}_t - \text{Out}_t$ where: S_t = Total carbon stock at time t mQ = Quantity of material m (mass or volume) mCF = Carbon fraction or carbon density of material m Σm = Summation over all material types In_t = Total inflow during period t Out_t = Total outflow during period t	Building inventories, construction/demolition data, material quantities, carbon factors	Makes storage visible; links urban form/infrastructure to carbon; supports circularity discussion	Often decoupled from operational emissions; sequestration weak; policy translation limited without integrated accounting
Sequestration/sink quantification (NBS)	Urban forests/greenspace sink models; biomass & soil carbon estimation; GIS/RS-supported quantification	$B = aD^b$ where: B = Biomass D = Diameter, e.g., tree diameter at breast height a = Scaling coefficient b = Allometric exponent	Remote sensing/GIS, land cover, field parameters, growth rates	Quantifies sinks; supports NBS justification; spatially explicit	High uncertainty/permanence issues; often isolated from emissions accounting; weak integration with temporal control and demand-side drivers
Integrated/hybrid coupling attempts	Emerging hybrid models combining inventories + sinks + stocks + scenarios (closest to DCM direction)	$\Delta S_t(t) = S_q(t) + \text{NetC}(t) - E(t)$ where: $\Delta S_t(t)$ = Change in carbon stock at time t $S_q(t)$ = Initial stock or pre-existing stock term at time t $\text{NetC}(t)$ = Net carbon uptake; positive if sequestration exceeds losses $E(t)$ = Emissions or carbon losses at time t	Multi-source data integration across scales + scenario assumptions	Most complete coverage; supports cross-scale integration; provides operational basis for "management" not just reporting	Still rare; lacks standardized coupling rules; limited implementation/validation; uncertainty propagation often weak

This static bias restricts the ability of existing approaches to capture:

- Non-linear interactions between urban development and carbon processes,
- Time-dependent effects of policy interventions,
- Delayed responses associated with sequestration, storage, or infrastructure transitions.

As a result, urban carbon assessments often function as retrospective diagnostics rather than tools capable of supporting adaptive or anticipatory decision-making.

3.2.2. Fragmentation of Carbon Processes within Analytical Frameworks

Another persistent limitation lies in the fragmented treatment of carbon processes. As demonstrated in Section 3, the literature tends to isolate carbon generation, transfer, sequestration, storage, and reduction into separate analytical streams. Even studies that acknowledge multiple processes typically address them in parallel, without establishing functional relationships or mutual dependencies.

This fragmentation manifests in several ways:

- Sequestration and storage are frequently assessed independently of emission sources,
- Transfer-based accounting expands spatial boundaries but disconnects carbon flows from urban form and land use,
- Reduction strategies are evaluated through scenarios without explicit linkage to underlying carbon stocks or sinks.

The absence of integrated process modeling limits the capacity of existing approaches to represent cities as coherent carbon systems, in which multiple processes interact across space and time.

3.2.3. Weak Treatment of Multi-Scale Interactions

Despite widespread recognition that cities operate across multiple spatial scales, most urban carbon studies adopt single-scale analytical perspectives as summarized in Table 6. City-level assessments dominate the literature, while building- and neighborhood-scale processes are either neglected or examined in isolation. Where scale transitions are addressed, they are typically handled through aggregation or disaggregation, rather than through explicit analytical coupling.

Key limitations include:

- Limited upward scaling of fine-grained data to inform city-level carbon balances,
- Weak downward translation of city-wide targets into building- or district-level actions,
- Absence of mechanisms to reconcile conflicting carbon dynamics across scales.

This weak treatment of scale inhibits the translation of carbon assessments into spatially differentiated planning and design strategies, reducing their practical relevance for urban intervention. These recurring limitations are synthesized in Table 6 and collectively highlight the need for explicit multi-scale coupling within future urban carbon management frameworks.

Table 6. Summary of scale-related limitations in existing urban carbon studies.

Scale Focus/Spatial Resolution (as Treated in Reviewed Studies)	Prevalence in Corpus (n, %)	What is Typically Captured at This Scale (from the Reviewed Papers)	Scale-Related Limitations Observed (What Consistently Fails When Scaling Up/Down)	Representative Studies from Uploaded Corpus
City-scale (city-level inventories/city metabolism/city carbon mapping)	23 (92%)	City-wide emission inventories; sectoral metabolism; city carbon balance; aggregate sequestration (urban forests/soils/green spaces); city-wide accounting frameworks and comparisons	(L1) Coarse aggregation masks intra-urban heterogeneity (hotspots, neighbourhood differences). (L2) Weak operational linkage to building/district interventions (hard to translate totals into actionable spatial design). (L3) Boundary inconsistency (administrative vs functional city) limits comparability. (L4) Often static snapshots with limited temporal dynamics/feedbacks	[1,2,11,17,33,52]
District/neighbourhood/ township scale	2 (8%)	Neighbourhood decarbonisation accounting frameworks; township-level accounting/management structuring	(L5) Scale boundary fragility (district delineation choices strongly change results). (L6) Poor upward compatibility to city totals without explicit coupling rules. (L7) Limited transferability across cities due to contextual parameters	[8,34]

Table 6. *Cont.*

Scale Focus/Spatial Resolution (as Treated in Reviewed Studies)	Prevalence in Corpus (n, %)	What is Typically Captured at This Scale (from the Reviewed Papers)	Scale-Related Limitations Observed (What Consistently Fails When Scaling Up/Down)	Representative Studies from Uploaded Corpus
Urban agglomeration/regional systems	2 (8%)	Multi-city accounting/prediction across agglomerations; spatiotemporal urbanization–carbon balance patterns	(L8) Downscaling deficit (regional totals rarely translate to urban-form/building levers). (L9) Functional interactions vs administrative units often unresolved. (L10) Spatial resolution varies (coarse grids/mixed data) causing interpretability loss for planning/design	[10,63]
Building-to-city (explicit building scale included alongside city scale)	1 (4%)	Building-related sequestration/storage accounting (e.g., carbon sequestration by urban buildings)	(L11) Rare explicit coupling: building carbon processes are rarely linked to city accounting in consistent aggregation logic. (L12) Data intensity & representativeness: building-level modelling often lacks scalable sampling designs	[7]
Global/national context used to interpret city carbon (global cities/national targets)	2 (8%)	Global-city metabolism comparisons; national-scale sequestration feasibility used as backdrop	(L13) Actionability gap: macro patterns provide limited guidance for spatial interventions. (L14) Mismatch of policy scale vs design scale without bridging constructs	[44,52]

3.2.4. Absence of Explicit Carbon Management Logic

Perhaps the most critical gap identified across the reviewed literature is the absence of an explicit carbon management logic. While carbon accounting methods provide valuable descriptive capabilities, they rarely incorporate mechanisms for active control, feedback, or adjustment. Management considerations are typically relegated to policy discussions or scenario narratives, rather than embedded as formal analytical components.

Consequently:

- Carbon indicators function primarily as reporting tools,
- Links between measurement and intervention remain implicit,
- Adaptive responses to changing urban conditions are weakly supported.

This absence limits the ability of current approaches to move beyond measurement-oriented paradigms toward frameworks capable of guiding continuous, responsive, and coordinated urban carbon action.

3.2.5. Limited Integration with Nature-Based and Spatial Planning Strategies

Finally, the review reveals a limited and uneven integration of nature-based solutions (NBS) and spatial planning strategies within urban carbon approaches. While numerous studies document the carbon sequestration potential of urban green infrastructure, these insights are seldom incorporated into comprehensive carbon accounting or management frameworks.

Common limitations include:

- Treatment of NBS as auxiliary or supplementary measures,
- Lack of spatial prioritization or optimization across urban contexts,
- Weak linkage between biophysical carbon benefits and planning decision processes.

This separation constrains the role of urban form, landscape design, and ecological systems in shaping long-term carbon trajectories.

3.2.6. Synthesis of Identified Gaps

Taken together, the reviewed literature reveals a set of interrelated limitations that collectively constrain the effectiveness of existing urban carbon approaches:

- Static rather than dynamic representations,
- Process fragmentation,

- Weak multi-scale integration,
- Absence of formal management logic,
- Limited coupling with spatial and nature-based strategies.

These gaps do not reflect a lack of methodological sophistication, but rather the absence of an overarching analytical structure capable of coordinating diverse carbon processes across time and space. Addressing these limitations requires moving beyond incremental refinements of existing accounting methods toward more integrative and operationally oriented conceptualizations of urban carbon systems.

3.3. Formalizing Dynamic Carbon Management (DCM)

The analytical synthesis and gap identification presented in the preceding sections indicate that prevailing urban carbon approaches are constrained by static representations, fragmented process treatment, weak scale integration, and the absence of explicit management logic. In response to these limitations, this study introduces and formalizes Dynamic Carbon Management (DCM) as an integrative conceptual framework designed to reorganize existing carbon constructs into a coherent, operational, and multi-scale system.

3.3.1. Conceptual Definition of Dynamic Carbon Management

Dynamic Carbon Management is defined as a process-oriented framework that conceptualizes urban carbon not as a set of isolated indicators, but as an interacting system of generation, transfer, sequestration, storage, and reduction processes, governed through adaptive management and feedback mechanisms over time. Unlike conventional accounting approaches that prioritize measurement and reporting, DCM emphasizes:

- Temporal dynamics, capturing how carbon processes evolve and interact across different time horizons;
- Process coupling, linking emissions, sinks, stocks, and transfers within a unified analytical structure;
- Operational applicability, enabling the translation of carbon information into actionable planning and management decisions.

In this sense, DCM does not seek to replace existing accounting methods, but rather repositions them as functional components within a broader management-oriented system.

3.3.2. Core Components of the DCM Framework

Building on the structured review, DCM is formalized around six interrelated components corresponding to the dominant carbon constructs identified in the literature:

1. Carbon Generation (G)

   Represents emissions arising from energy use, transportation, industry, and other urban activities. Within DCM, generation is treated as a dynamic variable influenced by urban form, infrastructure, and behavioral change.

2. Carbon Transfers (T)

   Captures embodied and virtual carbon flows associated with consumption, trade, and inter-regional linkages. DCM incorporates transfers to reflect the extended carbon footprint of urban systems beyond administrative boundaries.

3. Carbon Sequestration (S)

   Refers to active carbon uptake through biophysical processes, including urban vegetation, soils, and nature-based solutions. DCM integrates sequestration as a dynamic process rather than a static offset.

4. Carbon Storage (St)

   Encompasses carbon stocks accumulated in biomass, soils, and the built environment. Within DCM, storage functions as a temporal buffer that mediates short- and long-term carbon dynamics.

5. Carbon Reduction (R)

   Includes avoided emissions resulting from efficiency improvements, technological transitions, and planning interventions. DCM treats reduction as an outcome of coordinated management actions rather than isolated scenarios.

6. Carbon Management (M)

   Constitutes the central coordinating component of DCM, responsible for monitoring, feedback, and adaptive adjustment across all other processes. Management is formalized as an explicit analytical construct, rather than an implicit policy consideration.

3.3.3. Dynamic Relationships and Feedback Mechanisms

A defining feature of DCM is the explicit representation of feedback loops among carbon processes. Changes in one component such as reductions in generation or increases in sequestration alter system states and influence subsequent management decisions. These feedbacks enable DCM to support adaptive responses to evolving urban conditions, policy interventions, and external drivers.

Formally, DCM conceptualizes urban carbon dynamics as a time-dependent system in which:

- Carbon stocks evolve as a function of generation, sequestration, and reduction processes;
- Transfers modify local carbon balances through externalized emissions and imports;
- Management actions adjust system parameters based on monitored performance and predefined objectives.

This dynamic representation addresses the static bias identified in existing approaches and enables a more responsive understanding of urban carbon systems.

3.3.4. Distinction from Existing Urban Carbon Approaches

DCM differs from prevailing urban carbon approaches in several important respects:

- From accounting to management: while conventional methods focus on quantification, DCM prioritizes coordinated control and adjustment.
- From single-process analysis to system integration: DCM links multiple carbon processes within a unified framework.
- From single-scale assessment to multi-scale operability: DCM is explicitly designed to function across building, neighborhood, and city scales.
- From static snapshots to dynamic trajectories: DCM emphasizes temporal evolution and feedback.

These distinctions position DCM as a conceptual advancement rather than an incremental refinement of existing accounting logics.

3.3.5. Role of DCM within the Structured Review Context

Importantly, the formalization of DCM emerges directly from the structured review and analytical synthesis conducted in this study. The framework is not introduced as an abstract theoretical proposition, but as a logical response to empirically identified limitations in current urban carbon research. By reorganizing established constructs into a dynamic, management-oriented system, DCM provides a coherent foundation for addressing the fragmentation and operational gaps documented in the literature. The following section extends this formalization by examining how DCM can be operationalized across multiple spatial scales and integrated with urban planning, building systems, and nature-based strategies.

3.4. Multi-Scale Operational Mapping of Dynamic Carbon Management (DCM)

This section transforms the Dynamic Carbon Management (DCM) concept from a theoretical construct into an operational framework that clarifies how carbon-related processes can be dynamically coordinated across spatial scales. Rather than introducing new empirical evidence, the section formalizes an implementation logic that enables systematic integration of buildings, urban form, and nature-based solutions (NBS) within a multi-scale management structure as illustrated in (Figure 5).

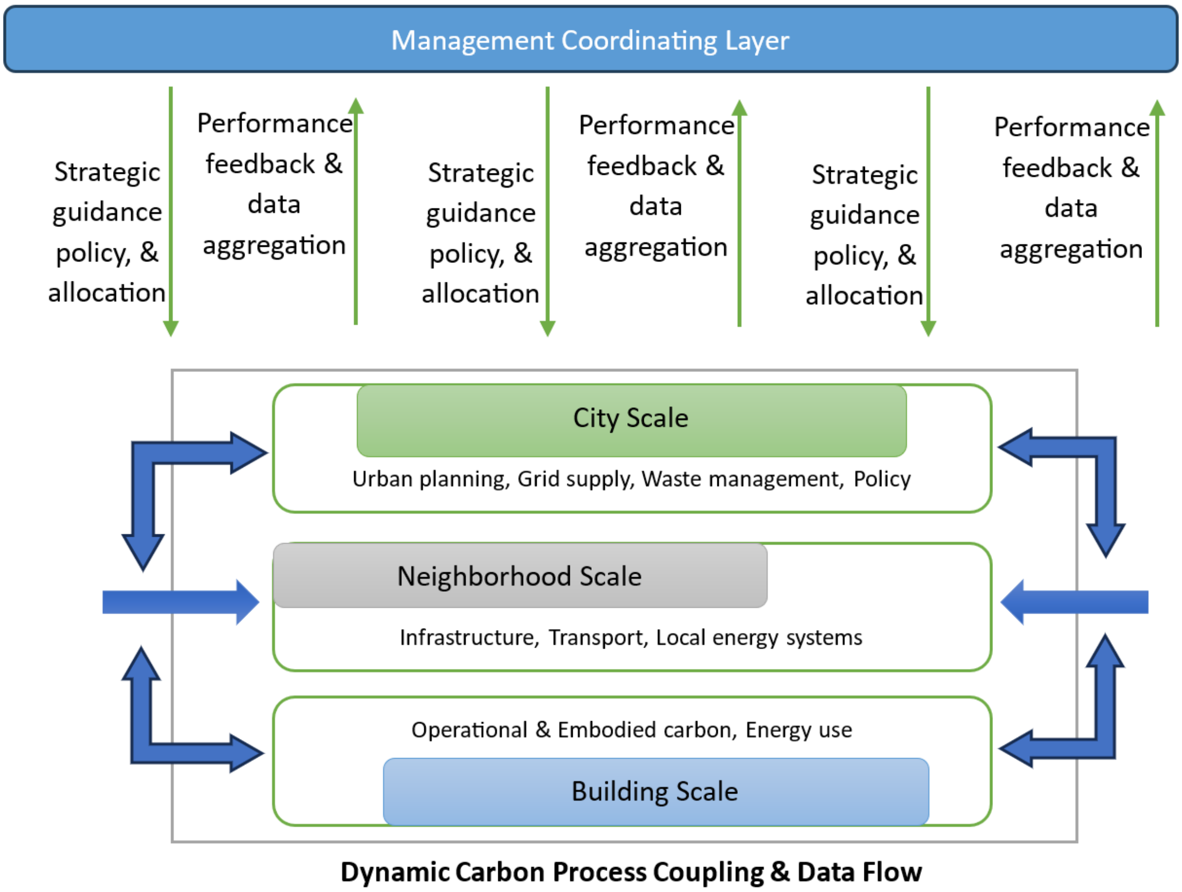

Figure 5. DCM Multi-Scale Operational Framework.

3.4.1. Operational Logic and Scale Hierarchy

DCM is structured around a hierarchical yet interactive scale system comprising the building, neighbourhood, and city levels. Each scale hosts distinct carbon processes generation, storage, sequestration, transfer, and reduction while remaining dynamically coupled through management and feedback mechanisms. At the building scale, carbon processes are primarily associated with operational energy use, material stocks, and micro-scale sequestration elements such as green roofs and façades. The neighbourhood scale aggregates these processes through spatial configuration, shared infrastructure, and distributed green networks, enabling collective performance beyond isolated building actions. At the city scale, carbon processes are expressed through sectoral emissions, large-scale ecological systems, and strategic mitigation pathways aligned with urban policy objectives. Crucially, DCM does not treat these scales as independent layers. Instead, it conceptualizes them as interdependent components within a dynamic management loop, where decisions at one scale propagate upward or downward, altering system-wide carbon performance.

3.4.2. Process–Scale Interaction Mapping

To operationalize this multi-scale logic, DCM requires an explicit mapping between carbon processes and spatial scales. This mapping clarifies where specific interventions act, how they interact with other processes, and which scale hosts primary responsibility for management and coordination.

Table 7 maps core carbon processes generation (G), sequestration (S), storage (St), transfer (T), and reduction (R) across spatial scales, highlighting scale-specific manifestations and management implications.

The table demonstrates that most existing urban carbon studies focus on a limited subset of processes at a single scale, typically emissions accounting at the city level or energy efficiency at the building level. DCM explicitly addresses this fragmentation by positioning management (M) as a cross-cutting function that coordinates interactions between processes and scales, rather than treating them as parallel or competing domains.

Table 7. Process–Scale Operational Mapping Matrix.

Process	Building Scale	Neighborhood Scale	City Scale
G	Energy use, systems	Mobility patterns	Sectoral emissions
S	Green roofs	Urban green networks	City-wide NBS
St	Material stocks	Biomass accumulation	Carbon reservoirs
T	Consumption patterns	Shared services	Inter-city flows
R	Retrofit measures	Spatial optimization	Strategic mitigation
M	Monitoring	Coordination	Adaptive governance

3.4.3. Stepwise Operational Workflow of DCM

Beyond structural mapping as illustrated in (Figure 6), DCM is designed to function through a stepwise operational workflow that supports iterative assessment, decision-making, and adjustment. This workflow does not prescribe a fixed computational model but establishes a consistent sequence through which diverse datasets, tools, and planning instruments can be aligned. The proposed workflow comprises the following stages:

1. Identification of dominant carbon processes at each scale;
2. Aggregation and normalization of multi-scale carbon-related data;
3. Assessment of interactions and trade-offs between processes and scales;
4. Management intervention and coordination across governance levels;
5. Performance evaluation using selected indicators;
6. Iterative refinement based on feedback and evolving targets.

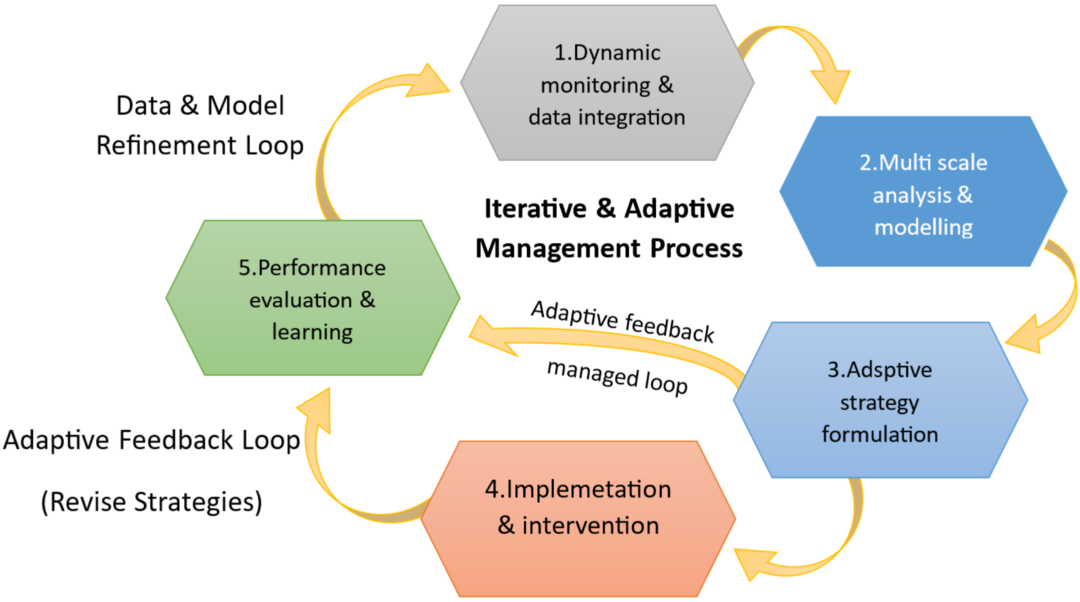

Figure 6. Stepwise Operational Workflow of DCM.

This workflow enables DCM to accommodate both short-term operational decisions and long-term strategic planning, while remaining flexible to data availability and institutional capacity.

3.4.4. Integration of Buildings, Urban Form, and Nature-Based Solutions

A defining feature of DCM is its capacity to integrate building-level decarbonization strategies, urban morphological characteristics, and nature-based solutions within a unified management framework. Rather than positioning NBS as supplementary measures, DCM treats them as integral components of the urban carbon system, contributing to sequestration, storage, and microclimatic regulation across scales. At the building scale, this integration includes envelope retrofitting, material selection, and localized greening. At the neighbourhood scale, it involves spatial continuity of green infrastructure and coordinated land-use patterns. At the city scale, it encompasses ecosystem-based planning and strategic alignment with climate targets. Indicative operational indicators commonly associated with these processes include emissions intensity (kg $CO_2e/m^2 \cdot yr$), sequestration capacity (t $CO_2e/ha \cdot yr$), carbon stock density (t C/ha), and reduction potential (%). While DCM does not impose specific metrics, its structure facilitates the consistent application and comparison of such indicators across scales.

3.4.5. Decision-Support Potential and Adaptability

By formalizing the relationships between carbon processes, spatial scales, and management functions, DCM functions as a decision-support framework rather than a prescriptive model. It enables planners and researchers to evaluate how interventions at one scale influence carbon performance at others, identify synergies and conflicts, and adapt strategies over time. Importantly, the framework is designed to be context-adaptive. It can be applied to cities with varying data resolution, governance structures, and climate priorities, making it suitable both as a comparative analytical tool and as a foundation for future empirical validation and modelling efforts.

4. Discussion

This section critically interprets the results of the structured review and analytical synthesis, evaluates the validity of the study's underlying propositions, and positions the proposed Dynamic Carbon Management (DCM) framework within the broader body of urban carbon research. Existing urban carbon studies often differ in their treatment of system boundaries, temporal dynamics, and the relative importance of operational emissions, embodied carbon, and ecological sequestration processes. While inventory-oriented approaches prioritize standardization and comparability, more recent system-based and dynamic perspectives emphasize interdependencies, temporal feedbacks, and multi-scale interactions. These differing perspectives partially explain the fragmentation identified in the reviewed literature and reinforce the need for more integrative management-oriented frameworks.

Validation of Core Research Propositions: The study was guided by three implicit propositions derived from gaps in the literature: 1) Urban carbon research is dominated by static accounting approaches rather than dynamic management logics. 2) Existing studies insufficiently integrate spatial scales, leading to fragmented and sometimes contradictory mitigation strategies. 3) Carbon sequestration and storage particularly through nature-based solutions are systematically underrepresented within urban carbon frameworks.

The structured review provides strong evidence in support of all three propositions. First, the overwhelming prevalence of emission-centric and inventory-based studies confirms that urban carbon is predominantly treated as a reporting variable rather than a system to be actively managed over time. While several studies employ advanced modelling or scenario analysis, these methods rarely translate into adaptive or feedback-driven management structures. This confirms that the shift from carbon accounting to carbon management is not merely semantic, but reflects a substantive theoretical gap. Second, the analysis of scale treatment demonstrates that most studies remain confined to single spatial resolutions, with limited methodological mechanisms for cross-scale integration. Even when multiple scales are acknowledged, they are often analysed sequentially rather than relationally. This supports the proposition that scale fragmentation is a structural limitation of current urban carbon research. Third, although nature-based solutions are increasingly discussed in urban sustainability literature, their role in carbon management remains analytically peripheral. The review shows that sequestration and storage are frequently treated as secondary co-benefits rather than core components of urban carbon systems. This fragmentation is also evident in recent carbon-sink literature, where measurement methods, system boundaries, and spatial scales remain poorly harmonized across building, district, and city-level applications [15,22]. This validates the need for frameworks that integrate ecological processes into carbon governance more explicitly. Recent empirical evidence from green-roof carbon monitoring further demonstrates that urban ecological systems can function as measurable and operational carbon sinks when integrated with district-scale accounting approaches [65].

Comparative Positioning Against Existing Frameworks: When compared with existing urban carbon frameworks, DCM differs in three fundamental ways. First, unlike conventional accounting frameworks that emphasize precision in measurement, DCM prioritizes functional coherence that is, how different carbon processes interact across space and time. This does not diminish the importance of accurate accounting; rather, it situates accounting as one component within a broader management logic. Second, in contrast to system metabolism or energy-flow models that often remain analytically abstract, DCM introduces an operational mapping logic, explicitly linking processes to spatial scales and intervention types. This enhances interpretability and practical relevance without relying on context-specific datasets. Third, DCM departs from mitigation-only paradigms by treating sequestration, storage, and emission reduction as co-evolving processes. This integrated perspective aligns more closely with emerging understandings of urban socio-ecological systems and responds to critiques that current decarbonization strategies are overly technocratic.

Theoretical Advancement: From a theoretical standpoint, the primary contribution of this study lies in reframing urban carbon as a managed dynamic system rather than a quantified outcome. While prior studies have addressed individual components of this system, few have attempted to formalize their interdependencies within a single conceptual structure. DCM contributes to theory in three ways: It introduces dynamism as a defining property of urban carbon systems, emphasizing temporal evolution and adaptive potential. It reconceptualizes scale as relational rather than hierarchical, enabling cross-scale reasoning. It embeds nature-based processes within the same analytical plane as built-environment interventions, challenging persistent dichotomies between technological and ecological solutions. These contributions extend beyond the synthesis of existing literature and represent a conceptual advancement that can inform future modelling, empirical studies, and policy design.

Implications for Urban Carbon Research and Practice: The findings suggest that continued reliance on static inventories and isolated mitigation strategies may limit the effectiveness of urban decarbonization efforts. Recent sub-municipal and high-resolution urban carbon studies also demonstrate the increasing transition from coarse city-wide inventories toward spatially differentiated and fine-grained carbon management approaches [30,32]. The applicability of DCM may vary across different urban contexts. In compact high-density cities, the framework may support the integration of building retrofits, district energy systems, and vertical greening strategies, whereas rapidly urbanizing cities may benefit more from its capacity to coordinate land-use expansion, infrastructure planning, and nature-based carbon sequestration. In this sense, DCM is intended as a flexible analytical and management structure rather than a fixed operational model. By contrast, DCM offers a framework capable of supporting: More coherent alignment between building-level interventions and city-wide carbon goals. Integrated evaluation of technological and ecological mitigation pathways. Adaptive carbon governance strategies responsive to urban growth, land-use change, and climate uncertainty.

Importantly, the framework does not prescribe specific solutions; instead, it provides a conceptual infrastructure upon which diverse methods and contexts can be systematically organized. The framework may also complement existing urban climate governance instruments, including carbon inventories, climate action plans, and carbon-neutrality roadmaps, by supporting more integrated and adaptive coordination across urban scales and carbon processes.

Critical Reflection and Scope of Contribution: It is essential to emphasize that this study does not claim empirical validation of DCM. Rather, its contribution lies in theoretical structuring and analytical synthesis. The framework should therefore be understood as a foundational construct, open to refinement, testing, and contextual adaptation. While recent studies have advanced dynamic simulation models, life-cycle carbon forecasting, and urban carbon-sink assessment, these approaches generally remain sector-specific or methodologically isolated, whereas DCM seeks to conceptually integrate carbon generation, mitigation, storage, and sequestration within a unified multi-scale management logic [14,31]. Previous reviews have typically focused on specific dimensions of urban carbon research, including greenhouse gas accounting methods, building-sector decarbonization, urban metabolism, or nature-based carbon sequestration. In contrast, the present study attempts to analytically connect these previously fragmented dimensions within a unified multi-scale management perspective, thereby extending the discussion from carbon accounting toward dynamic carbon management. This positioning is deliberate and aligns with the nature of the research design. By grounding DCM in a rigorous review of existing literature, the study avoids speculative theorization while still advancing a novel conceptual direction. This perspective aligns with growing calls for more rigorous urban carbon accounting principles and integrated governance structures capable of supporting long-term carbon neutrality transitions across urban systems [9,33].

Limitations and Future Research

Despite the conceptual and analytical contributions of this study, several limitations should be acknowledged to clarify the scope of its findings and to guide subsequent research efforts. First, this study is based on a structured analytical review rather than a full systematic review or empirical investigation. Although the review protocol was carefully designed and transparently articulated, it does not claim exhaustive coverage of all urban carbon studies, nor does it apply statistical meta-analysis techniques. As such, the synthesized patterns and distributions should be interpreted as representative rather than definitive. Future research may expand the dataset using fully systematic review protocols or bibliometric analyses to further validate and refine the identified trends. Second, the proposed Dynamic Carbon Management (DCM) framework remains conceptual and non-empirical at this stage. While the framework is grounded in extensive literature synthesis and analytical reasoning, it has not yet been tested through real-world case studies, simulations, or quantitative modelling. Empirical validation across different urban contexts such as compact cities, rapidly urbanizing regions, or climate-vulnerable urban areas represents a critical next step to assess the operational feasibility and performance of DCM in practice.

Third, although the framework explicitly emphasizes multi-scale integration, the current study does not model quantitative interactions across spatial scales. The relationships between building-level interventions, neighborhood-scale nature-based solutions, and city-wide carbon balances are conceptually articulated but not numerically parameterized. Future work could operationalize these linkages using integrated urban energy models, spatial carbon accounting tools, or coupled GIS–simulation approaches. Fourth, the review primarily focuses on carbon-related processes, while broader sustainability dimensions such as economic costs, social equity, institutional capacity, and governance mechanisms are only indirectly addressed. Given that urban carbon management is inherently socio-technical, future research should explore how DCM interfaces with governance structures, policy instruments, and stakeholder decision-making processes, particularly in diverse regulatory and cultural contexts. Finally, the scope of nature-based solutions in this study is intentionally framed around carbon sequestration and storage. However, NbS generate multiple co-benefits, including thermal regulation, biodiversity enhancement, and public health improvement. Integrating these co-benefits into dynamic carbon management frameworks remains an open research avenue that could further strengthen the relevance of DCM for holistic urban sustainability planning.

Future Research Directions: Building on these limitations, several priority directions for future research emerge: First, the proposed DCM framework requires empirical validation through application to real urban systems and comparative case studies across different urban typologies. Second, future studies may explore the integration of DCM with urban simulation tools, digital twins, GIS-based carbon mapping, and dynamic monitoring systems to improve operational applicability. Third, further methodological development is needed to quantitatively model interactions between carbon generation, mitigation, storage, and sequestration across multiple spatial and temporal scales. Finally, future research may investigate how DCM can be incorporated into urban climate governance, carbon-neutrality planning, and adaptive policy frameworks under different socio-economic and climatic conditions.

5. Conclusions

This study set out to critically examine how urban carbon has been conceptualized, quantified, and addressed in the existing literature, while also assessing whether current approaches are sufficient to support effective urban decarbonization. Through a structured analytical review of urban carbon studies, the research demonstrates that prevailing approaches remain largely fragmented, static, and scale-bound, with primary emphasis placed on carbon accounting rather than carbon management. The synthesis reveals three persistent limitations across the literature: the dominance of emission-centric accounting logics, the weak integration of spatial scales, and the marginalization of carbon sequestration and storage, particularly through nature-based solutions within urban carbon frameworks. Collectively, these limitations constrain the capacity of existing approaches to inform integrated, adaptive, and spatially responsive carbon strategies. In response to these findings, the paper introduces Dynamic Carbon Management (DCM) as a conceptual advancement grounded in the reviewed evidence. DCM reframes urban carbon as a multi-process, multi-scale system that evolves over time and requires coordinated and adaptive management rather than isolated measurement. By integrating carbon generation, accounting, storage, sequestration, and mitigation within a unified analytical structure, the framework offers a coherent logic for linking building-level actions, urban form, and ecological interventions to city-wide carbon objectives. Importantly, this study does not claim empirical validation of the proposed framework. Instead, its contribution lies in providing a theoretically grounded and analytically derived structure that clarifies relationships between urban carbon processes and identifies pathways for future operationalization. As such, DCM should be understood as a foundational framework capable of guiding subsequent empirical studies, modelling efforts, and policy-oriented applications. Overall, the paper advances urban carbon research by shifting the focus from fragmented accounting practices toward an integrated management perspective. By doing so, it contributes to ongoing efforts to align urban planning, building design, and nature-based strategies within coherent decarbonization pathways, while also offering a conceptual platform for future research addressing the dynamic and multi-scalar nature of urban carbon systems.

Author Contributions

A.A.N.A.: Conceptualization, methodology, formal analysis, investigation, visualization, writing—original draft, writing—review and editing, project administration, and corresponding author. A.F.K.: Validation, investigation, writing—review and editing. K.M.A.: methodology, writing—review and editing. A.A.A.A.-N.: Investigation, validation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

This study is based exclusively on published literature and secondary analytical sources. It does not involve human participants, personal data, surveys, interviews, or experimental procedures. Therefore, ethical approval was not required.

Data Availability Statement

All information analyzed is derived from publicly available published literature, and the corresponding references are provided in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editorial Board Member, Akram Ahmed Noman Alabsi had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) and DeepL for language editing. after using these tools, the authors carefully reviewed and edited the manuscript as needed and take full responsibility for the content of the published article.

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