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Multifunctional roles of urban green spaces in carbon sequestration, water filtration, and biodiversity conservation: A comprehensive review

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Abstract

Urban green spaces (UGS) have emerged as critical ecological infrastructures that contribute significantly to environmental sustainability in rapidly urbanizing regions. This review synthesizes findings from 18 high-quality original research studies to evaluate the role of UGS in carbon sequestration, water filtration, and biodiversity conservation. The analysis reveals that urban vegetation serves as an effective carbon sink through biomass accumulation and soil organic carbon storage, though sequestration capacity is strongly influenced by species composition, age structure, and management practices. In terms of hydrological functions, green spaces improve water quality by enhancing infiltration, reducing surface runoff, and facilitating the removal of pollutants through biological and physicochemical processes. Additionally, UGS provide essential habitats for flora and fauna, supporting species richness and ecological connectivity in fragmented urban landscapes. However, inconsistencies across studies highlight variability in ecosystem service delivery due to spatial heterogeneity, socio-economic disparities, and climatic conditions. The review identifies key research gaps, including insufficient long-term monitoring, limited integration of ecosystem services, and underrepresentation of tropical and developing regions. Future research should focus on multifunctional landscape planning, climate adaptation strategies, and policy integration to optimize ecosystem service delivery. Overall, urban green spaces play a vital role in enhancing environmental resilience and promoting sustainable urban development.

Keywords: Biodiversity conservation, carbon sequestration, ecosystem services, green infrastructure, urban ecology, urban forests, urban resilience, water purification

Introduction

Urbanization has accelerated dramatically over the past century, resulting in significant alterations to natural ecosystems and biogeochemical cycles. Increasing urban expansion has contributed to elevated greenhouse gas emissions, degradation of water quality, and substantial biodiversity loss, thereby intensifying environmental challenges at local and global scales (Grimm *et al.*, 2008) ^[3]. In response to these concerns, urban green spaces (UGS) have gained recognition as essential components of sustainable urban systems due to their capacity to provide critical ecosystem services (Tzoulas *et al.*, 2007) ^[32]. Urban green spaces encompass a diverse range of vegetated areas, including parks, street trees, urban forests, wetlands, and green roofs. These systems contribute to environmental regulation through carbon sequestration, hydrological balance, and habitat provision (Bolund & Hunhammar, 1999) ^[4]. Among these functions, carbon storage is particularly important in mitigating climate change, as vegetation captures atmospheric carbon dioxide and stores it in biomass and soils (Nowak & Crane, 2002) ^[21]. Simultaneously, green infrastructure plays a key role in improving water quality by enhancing infiltration and reducing pollutant loads in stormwater runoff (Paul & Meyer, 2001) ^[23]. Urban biodiversity has also become a focal point in ecological research, as cities increasingly serve as habitats for various species despite high levels of disturbance. Green spaces act as ecological refuges, supporting species diversity and promoting ecosystem resilience (McKinney, 2008) ^[20]. However, the effectiveness of these services is influenced by spatial configuration, vegetation diversity, and management practices (Pickett *et al.*, 2011) ^[24]. Although numerous studies have examined individual ecosystem services, there is a lack of comprehensive synthesis

addressing their combined roles within urban landscapes. This review aims to bridge this gap by integrating findings from multiple empirical studies to evaluate the multifunctional contributions of urban green spaces, with a focus on carbon sequestration, water filtration, and biodiversity conservation.

2. Methodology

2.1 Literature Search Strategy

A systematic literature review was conducted using databases such as ResearchGate, Scopus, Web of Science, and Google Scholar. Search terms included “urban green spaces,” “carbon sequestration urban forests,” “stormwater filtration green infrastructure,” and “urban biodiversity conservation” combined using Boolean operators (Kabisch *et al.*, 2015) ^[17].

2.2 Inclusion Criteria

Studies were selected based on the following conditions:

- Published between 2010 and 2024,
- Peer-reviewed original research articles,
- Focused on urban or peri-urban ecosystems,
- Addressed at least one ecosystem service under Consideration, and
- Included empirical data with clear methodologies (Haase *et al.*, 2015) ^[17].

2.3 Exclusion Criteria

Studies excluded from the review included conceptual papers, review articles, and research lacking methodological clarity or empirical evidence (Elmqvist *et al.*, 2013) ^[10].

2.4 Data Extraction and Analysis

A total of 18 studies were selected and analyzed. Data extracted included study objectives, methodology, ecosystem services assessed, and key findings. A thematic synthesis approach was used to categorize findings into carbon sequestration, water filtration, and biodiversity conservation (Haaland & van den Bosch, 2015) ^[14].

3.1 Carbon Sequestration in Urban Green Spaces

3.1.1 Aboveground Biomass Carbon Storage

Urban vegetation plays a critical role in capturing atmospheric carbon dioxide through photosynthesis and storing it in plant biomass. Urban forests, in particular, have been identified as significant carbon sinks, with their capacity largely determined by tree density, species composition, and age structure (Nowak *et al.*, 2014) ^[22]. Large, mature trees contribute disproportionately to carbon storage due to their extensive biomass accumulation (McHale *et al.*, 2009) ^[19]. Species selection also influences sequestration efficiency, as different species exhibit varying growth rates and carbon assimilation capacities. Fast-growing species tend to accumulate carbon rapidly, whereas slow-growing hardwood species provide long-term storage stability (Churkina *et al.*, 2010) ^[6]. Mixed-species plantings have been shown to enhance productivity and carbon capture due to niche complementarity and reduced competition (Pretzsch *et al.*, 2015) ^[26].

Urban conditions, including pollution, soil compaction, and limited rooting space, can restrict tree growth and reduce carbon sequestration potential (Jim, 2012). Therefore, appropriate species selection and urban forestry

management practices are essential to maximize carbon storage (Table 1) (Figure1).

3.1.2 Belowground Carbon Storage

Soil organic carbon (SOC) represents a major component of carbon storage in urban ecosystems. Studies indicate that urban soils can store carbon levels comparable to those of natural ecosystems when managed effectively (Edmondson *et al.*, 2014) ^[9]. Organic matter inputs from leaf litter, root biomass, and microbial activity contribute to SOC accumulation. However, urban soils often experience disturbances such as compaction, excavation, and contamination, which negatively impact their carbon storage capacity (Pouyat *et al.*, 2010) ^[25]. Management practices such as mulching, reduced tillage, and organic amendments can enhance SOC levels and improve soil health.

3.1.3 Influencing Factors and Spatial Variability

Carbon sequestration in UGS is influenced by environmental, biological, and socio-economic factors. Climatic conditions, including temperature and precipitation, affect vegetation growth and carbon uptake (Zhao *et al.*, 2018) ^[31]. Land-use patterns and urban planning decisions also determine the distribution and extent of green spaces. Spatial variability in carbon storage is significant, with urban centers often exhibiting lower sequestration potential compared to suburban areas due to limited green cover (Davies *et al.*, 2011) ^[7]. Understanding these variations is essential for optimizing carbon management strategies.

3.2 Water Filtration and Hydrological Functions

3.2.1 Stormwater Management

Urbanization increases impervious surface cover, leading to reduced infiltration and increased surface runoff. Green spaces mitigate these effects by intercepting rainfall and promoting infiltration, thereby reducing flood risks (Shuster *et al.*, 2009) ^[27]. Green infrastructure elements such as bioswales, rain gardens, and permeable pavements enhance stormwater management by mimicking natural hydrological processes (Dietz, 2007) ^[8]. Vegetation slows down water flow, allowing sediments and pollutants to settle (Figure2).

3.2.2 Pollutant Removal Processes

Urban runoff contains contaminants such as heavy metals, nutrients, and organic pollutants. Green spaces remove these pollutants through filtration, adsorption, and biological degradation (Vijayaraghavan *et al.*, 2017) ^[29]. Soil microorganisms play a key role in breaking down organic pollutants, while plant roots facilitate nutrient uptake. Wetlands are particularly effective in nutrient removal due to anaerobic conditions that promote denitrification (Zedler & Kercher, 2005) ^[30].

3.2.3 Groundwater Recharge and Water Balance

Green spaces contribute to groundwater recharge by facilitating infiltration. This process is essential for maintaining urban water supply and reducing dependency on external sources (Berland *et al.*, 2017) ^[3]. However, the effectiveness of groundwater recharge depends on soil permeability, vegetation cover, and land management practices. Urban planning strategies should prioritize permeable surfaces to enhance water sustainability.

3.3 Biodiversity Conservation in Urban Landscapes

3.3.1 Habitat Provision and Ecological Niches

Urban green spaces provide habitats for diverse species, including plants, birds, insects, and mammals. The structural complexity of vegetation enhances habitat quality by offering food resources, shelter, and nesting sites (Goddard *et al.*, 2010) ^[12] (Table 2). Different types of green spaces support varying species assemblages. For example, urban forests support bird diversity, while wetlands provide habitats for amphibians and aquatic organisms.

3.3.2 Species Richness and Connectivity

Species richness in urban areas is influenced by the size, quality, and connectivity of green spaces. Larger and well-connected habitats support higher biodiversity levels (Beninde *et al.*, 2015) ^[2]. Green corridors facilitate species movement and gene flow, reducing the effects of habitat fragmentation (Haddad *et al.*, 2015) ^[15]. Connectivity is therefore a key factor in maintaining ecological resilience.

3.3.3 Role of Native and Exotic Species

Native plant species are more effective in supporting local biodiversity, as they co-evolved with native fauna (Burghardt *et al.*, 2009) ^[5]. In contrast, exotic species may provide limited ecological benefits. However, urban landscapes often include ornamental plants, which may not support ecosystem functions effectively. Integrating native species into urban design can enhance biodiversity outcomes (Figure 3).

4. Results and Discussion

The synthesis of selected studies demonstrates that urban

green spaces provide multiple ecosystem services simultaneously (Table 3). Carbon sequestration, water filtration, and biodiversity conservation are interconnected processes that collectively enhance urban sustainability (Elmqvist *et al.*, 2015) ^[11]. Despite these benefits, variability exists in ecosystem service delivery due to differences in climate, land use, and socio-economic conditions. Some studies report high carbon storage in urban forests, while others highlight limitations due to space constraints and management practices (Strohbach & Haase, 2012) ^[28]. Water filtration effectiveness depends on the design and maintenance of green infrastructure systems. Poorly maintained systems may lose efficiency over time. Similarly, biodiversity benefits are influenced by habitat quality and connectivity. A major gap identified is the lack of integrated studies examining multiple ecosystem services simultaneously. Most research focuses on individual functions, limiting the understanding of trade-offs and synergies.

5. Future Challenges and Directions

Future research should focus on integrated assessments of ecosystem services, long-term monitoring, and the application of advanced technologies such as GIS and remote sensing (Kabisch *et al.*, 2016) ^[18]. There is also a need to incorporate socio-economic factors into urban planning to ensure equitable access to green spaces. Climate change presents additional challenges, requiring adaptive management strategies to maintain ecosystem services under changing conditions. Policymakers should prioritize green infrastructure development as part of sustainable urban planning.

Table 1: Types of Urban Green Spaces and Their Ecosystem Functions

S. No.	Type of Green Space	Carbon Sequestration	Water Filtration	Biodiversity Support
1	Urban forests	High	Moderate	High
2	Parks and gardens	Moderate	Moderate	Moderate
3	Green roofs	Low-Moderate	High	Low-Moderate
4	Wetlands	High	Very High	Very High
5	Riparian buffers	High	High	High

Citation: Bolund & Hunhammar (1999) ^[4]; Nowak *et al.* (2014) ^[22]

Table 2: Mechanisms of Ecosystem Services in Urban Green Spaces

S. No.	Function	Mechanism	Key Components Involved
1	Carbon sequestration	Photosynthesis and biomass accumulation	Trees, shrubs, soil organic C
2	Water filtration	Infiltration, adsorption, microbial degradation	Soil, roots, microbes
3	Biodiversity	Habitat provision and connectivity	Flora, fauna, microhabitats

Citation: Tzoulas *et al.* (2007) ^[32]

Table 3: Quantitative Benefits of Urban Green Spaces

S. No.	Ecosystem Service	Indicator	Typical Range/Impact
1	Carbon storage	t C ha ⁻¹	30-300 (urban forests)
2	Carbon sequestration	t C ha ⁻¹ yr ⁻¹	1-10
3	Water filtration	% runoff reduction	20-80%
4	Biodiversity	Species richness increase	10-50% higher than built areas

Citation: Livesley *et al.* (2016) ^[33]

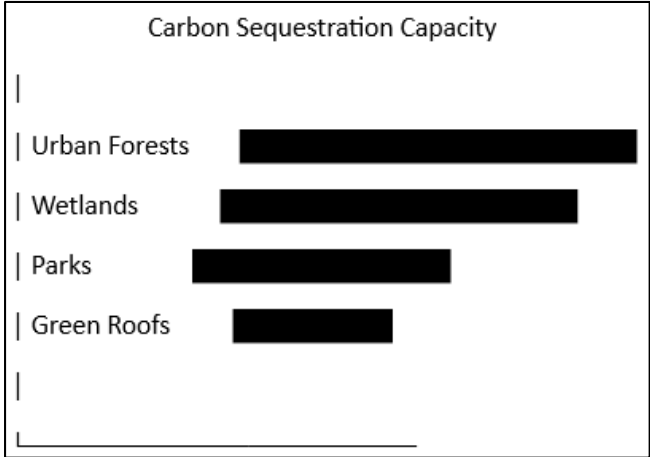


Fig 1: Carbon Sequestration Potential across Urban Green Spaces

Interpretation

Urban forests and wetlands act as major carbon sinks due to higher biomass and soil carbon storage.

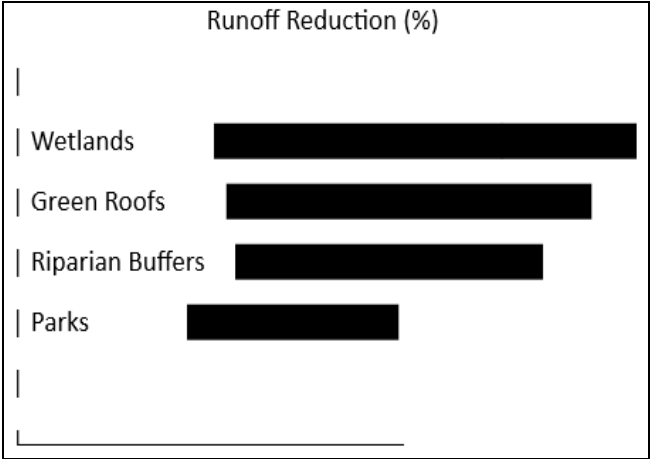


Fig 2: Water Filtration Efficiency of Green Infrastructure

Interpretation

Constructed wetlands and green roofs are highly efficient in reducing urban runoff and improving water quality.

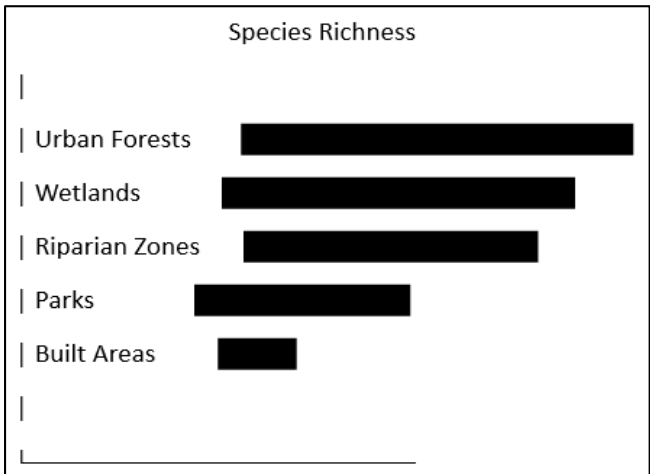


Fig 3: Biodiversity Enhancement in Urban Green Spaces

Interpretation

Urban green spaces significantly increase biodiversity compared to built environments.

6. Conclusions

Urban green spaces play a vital role in enhancing environmental sustainability by providing essential ecosystem services. This review highlights their multifunctional contributions to carbon sequestration, water filtration, and biodiversity conservation. Despite their importance, challenges such as spatial variability, limited research integration, and policy gaps remain. Addressing these issues will require interdisciplinary approaches and effective urban planning strategies.

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