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Research on the Potential of Urban Green-Blue Infrastructure in Carbon Reduction Benefits

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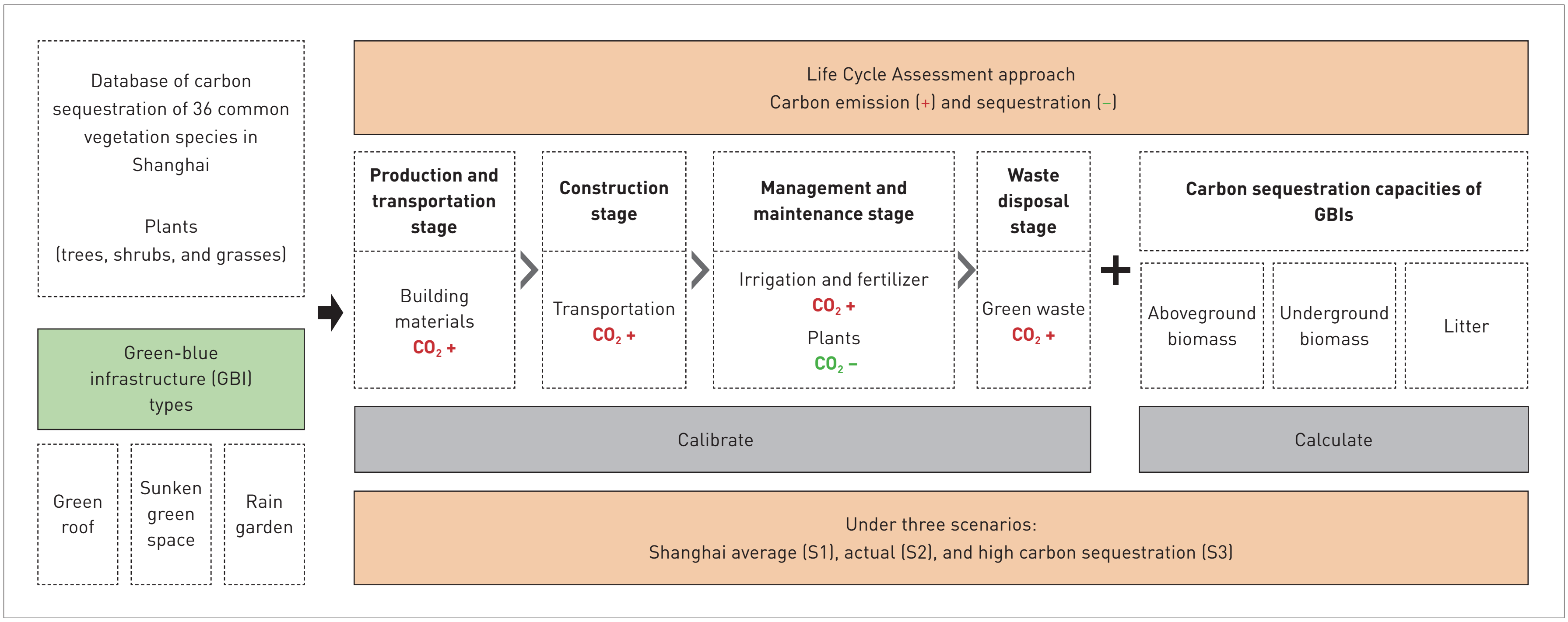
GRAPHICAL ABSTRACT



ABSTRACT

Urban green-blue infrastructures (GBIs) are increasingly gaining attention in the pursuit of carbon neutrality, particularly within residential areas. With this background, this study established an integrated quantitative framework to assess both direct and indirect carbon reduction benefits of urban GBIs, by leveraging Life Cycle Assessment approach to precisely calibrate the carbon sequestration benefits of three typical urban GBIs (green roofs, sunken green spaces, and rain gardens) under three different scenarios and building a carbon sequestration database that includes 36 local plant species in Shanghai. The research results indicate that GBIs have a reducing effect on carbon emissions in urban residential areas. If extrapolating the simulation results to the city scale, the preliminary estimation suggests that the construction of GBIs within residential areas in Shanghai can achieve a carbon sink of approximately 540.54 million tCO_2eq per year. This level of carbon sequestration is equivalent to 32% of Shanghai's annual carbon emissions. It is evident that the construction of GBIs possesses significant potential in carbon reduction benefits and for achieving urban carbon neutrality strategies.

KEYWORDS

Green-Blue Infrastructure; Life Cycle Assessment; Planting Design; Green-Blue Infrastructure Design; Carbon Reduction Benefit; Carbon Sequestration; Residential Area

HIGHLIGHTS

- Develops an integrated quantitative framework for assessing direct and indirect carbon reduction benefits of urban green-blue infrastructure (GBI)
- Builds a carbon sequestration database including 36 local plant species in Shanghai and uses Life Cycle Assessment approach to quantify carbon sequestration benefits of GBI
- Preliminarily estimates that the carbon sequestration by the construction of GBIs within residential areas in Shanghai is equivalent to 32% of Shanghai's annual carbon emissions
- Proposes optimized combinations of trees, shrubs, and grasses for effective GBI design

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1 Introduction

1.1 Overestimated Carbon Sequestration Capabilities of Urban Green-Blue Infrastructure

Building climate resilience has emerged as a crucial strategy for urban areas grappling with climate change risks. Green-blue infrastructure (GBI) encompasses strategically planned natural or semi-natural land and water areas[1][2]. These spaces are intentionally designed and managed to provide ecosystem services, including air and water purification, local temperature regulation, and climate mitigation and adaptation[3]. By enhancing ecosystem resilience and human well-being, GBI becomes an essential tool for bolstering urban resilience and adapting to dynamic living environments[4]. Unlike traditional hard-engineered facilities (e.g., roads, drainage systems, pipelines), GBI forms a structurally elastic system through the integration of vegetation and water elements[5].

The carbon sequestration of GBIs is thought to play a pivotal role in establishing energy-efficient and emission-reducing systems within residential areas. Through photosynthesis, broad-leaved forests can sequester approximately 360 tCO_2eq per hectare annually[6]. Urban GBIs not only ensure carbon sequestration within residential green spaces but also deliver significant cooling effects[7][8]. However, focusing solely on the carbon sequestration of vegetation within GBIs may overlook the release of greenhouse gases during the construction and waste disposal phases, which consequently could lead to an overestimation of the carbon sequestration impact of GBIs[9]. It is needed to investigate the relationship between GBI and its carbon sequestration in residential areas through quantitative analysis methods.

Besides, existing research indicated that calculations of the carbon sequestration of GBIs should not only consider the benefits to the infrastructure but should also consider all GBI systems as a whole[10]. While studies have explored the use of GBIs as standalone ecosystems for carbon sequestration, research on specific GBIs remains limited. The majority of the research has concentrated on green roofs, with other GBI types receiving less attention regarding their carbon sequestration capabilities. Furthermore, although there is a general categorization of plant selection for GBIs, according to the *Technical Guide for Sponge City Construction (Trial)*[11], detailed studies on refined classification and vegetation combinations are sparse. There is a clear need for the development of a more comprehensive database to support such research.

1.2 GBIs' Carbon Reduction Benefits for Urban Residential Areas

The construction industry is a significant contributor to energy consumption and carbon emissions[12]. In China, the total carbon emissions from the entire process of building construction account for 38.2% of the country's energy related carbon emissions[13]. When considering associated energy expenditures, such as the production and transport of steel, cement, glass, and masonry materials, the construction industry's total energy consumption soars to 46.7%[14], with building CO_2 emissions constituting roughly 40% of China's overall carbon emissions[15]. Nonetheless, the construction industry holds substantial potential for energy conservation and emission reduction. A report revealed that, with judicious energy-saving design and scientific management, building energy efficiency can achieve 30% ~ 70% savings[16]. Thus, the construction industry not only is pivotal in controlling and reducing greenhouse gas emissions but also plays an essential role in advancing research on energy conservation and carbon reduction in residential areas. Numerous studies have highlighted the significant potential of GBI construction for energy savings and carbon reduction benefits[17]~[23].

Among various GBI types, green roofs, sunken green spaces, and rain gardens have been thoroughly researched and shown clear benefits in reducing carbon emissions for buildings. Green roofs, for example, foster carbon sequestration and emission reduction through both direct and indirect effects. Directly, they absorb atmospheric CO_2 through the interaction between vegetation and the soil matrix[17][18]; while, indirectly, the shading and transpiration effects of vegetation and soil on green roofs can reduce the temperature around buildings and help restrain the heat gain or loss process of buildings, thereby reducing the heating and cooling costs, improving the energy-saving performance of buildings, and extending the life of the building[19]. Therefore, the carbon reduction benefits of GBIs are crucial for carbon reduction and have gradually attracted the attention of the academia. However, when studying the carbon reduction benefits of GBI, current research mainly focuses on large-scale urban blue-green spaces[24][25], lacking quantitative models for studying the indirect carbon reduction benefits of GBI within residential areas.

This study aims to construct an integrated quantitative framework for direct and indirect carbon reduction benefits of urban GBIs by firstly calibrating the overestimation caused by counting only the carbon sink in management and maintenance stage through a Life Cycle Assessment (LCA) approach for typical urban GBIs and secondly establishing a vegetation database that refines the selection of 36 plant species (including two lawn grass species) and various landscape combinations of trees, shrubs, and grasses for GBI.

2 Research Methods

2.1 Study Area and Scenario Setting

The research chose a residential area, Vanke Jiading Future City, in Shanghai as the case study, which covers a total green space of 77,390.2 m^2. The existing design drawings allocate 37,206.5 m^2 for sunken green spaces, 21,323.9 m^2 for green roofs, and 18,859.8 m^2 for rain gardens. This study is to provide a comprehensive assessment on the carbon emission and carbon sequestration during the implementation of GBIs by proposing three distinct scenarios based on different types of GBIs—green roofs, sunken green spaces, and rain gardens—and their associated vegetation combinations.

1) Scenario 1 (S1, Shanghai average): this scenario adheres to common planting types and proportions of supporting vegetation typically found in Shanghai's residential areas. The distribution of trees, shrubs, and grass follows the research by Yuefeng Han[26]. Specifically, sunken green space and rain garden both take a proportion of 2:6:2 (trees:shrubs:grass), and green roofs exclusively feature grass.

2) Scenario 2 (S2, actual): this scenario reflects the actual planting types and proportions observed in the study area, and the data were extracted from the CAD drawings of site planting design.

3) Scenario 3 (S3, high carbon sequestration): this scenario adopts the proportion of high-carbon sequestration vegetation within the GBIs based on the actual construction of the residential area.

The vegetation combinations for the three types of GBIs under the three scenarios are outlined in Table 1.

2.2 Integrated Quantitative Framework for Urban GBIs' Direct and Indirect Carbon Reduction Benefits

The integrated quantitative framework of the carbon emissions and sequestration for typical urban GBIs—i.e. green roofs, sunken green spaces, and rain gardens—proposed in this research consists of two parts. The first is to calibrate the overestimation caused by counting only the carbon sink in management and maintenance stage. Considering that, in addition to carbon sequestration benefits, the carbon emissions generated by GBIs in the upstream process cannot be ignored, the LCA approach is chosen for this study. This is an internationally standardized, effective tool for evaluating the energy consumption and environmental impact of a product, process or service in the whole life cycle stage from raw

Table 1: Vegetation combination of different GBI facilities under the three scenarios

GBI type	Vegetation proportion (tree:shrub:grass)	Tree area (m^2)	Shrub area (m^2)	Grass area (m^2)
		S1		
SGS	2:6:2	7,441.3	22,323.9	7,441.3
GR	0:0:10	0	0	21,323.9
RG	2:6:2	3,771.95	11,315.85	3,771.95
Total	—	**11,213.25**	**33,639.75**	**32,537.15**
		S2		
SGS	1.8:7.2:1	6,697.17	26,788.68	3,720.65
GR	0:6:4	0	12,794.34	8,529.56
RG	2:6:2	3,771.95	11,315.85	3,771.95
Total	—	**10,469.12**	**50,898.87**	**16,022.16**
		S3		
SGS	1.8:7.2:1	6,697.17	26,788.68	3,720.65
GR	3.4:4.7:1.9	7,250.13	10,022.23	4,051.54
RG	2:6:2	3,394.76	13,579.02	1,885.98
Total	—	**17,342.06**	**50,389.93**	**9,658.17**

NOTES

1. SGS = sunken green space; GR = green roof; and RG = rain garden.
2. Because the green spaces in the study area includes areas for constructing pedestrian walkways, seating, decorative structures, etc., the total area of trees, shrubs, and grasses is less than the total area of the green spaces.

material collection to product production, transportation, use, and final disposal[27]~[29]. By systematically assessing environmental impacts, LCA highlights the significance of environmental factors and guides the implementation of measures to reduce impact at various stages, aligning with sustainable development goals[30]. Considering a 50-year accounting boundary[31], this study divides GBI's life cycle into four stages: production and transportation (P & T stage), construction (C stage), management and maintenance (M & M stage), and waste disposal (WD stage). The second is to establish a vegetation database that refines the selection of 36 plant species, as well as various combinations of trees, shrubs, and grasses, for calculating the carbon sequestration capacities of GBIs, demonstrating with a case study on a residential area in Shanghai (Fig. 1).

2.3 Calibrating the Overestimation by Incorporating the LCA Approach

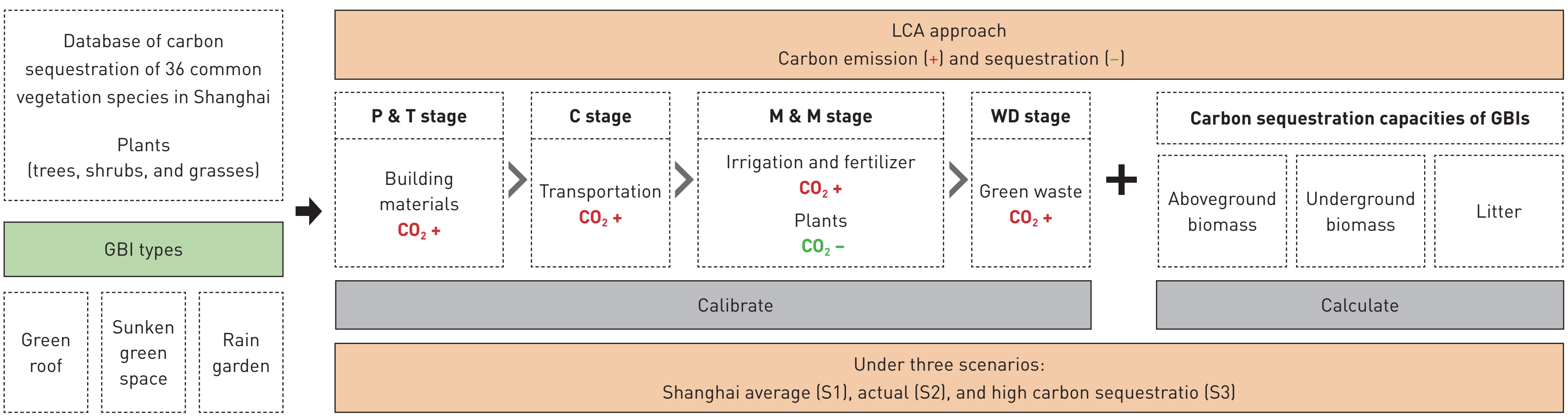
2.3.1 The P & T Stage

In the P & T stage, carbon emissions arise from two primary sources[32]. The first is both the direct and indirect emissions associated with the materials used in construction, originating from mining, production, and other upstream processes; and the second pertains to the emissions produced during the transportation of building and vegetation materials integral to GBIs. The calculation method for carbon emissions from the material production is shown in Eq. (1)[33]:

$$E^{m}_{CO_2} = \sum_i \left(Q^{m}_{i} \times EF^{m}_{CO_{2,i}} \right), \tag{1}$$

where m stands for material and i represents the type of material; $E^{m}_{CO_2}$ is the CO_2 emission of the material i in the upstream production; Q^{m}_{i} is the consumption of material i; and $EF^{m}_{CO_{2,i}}$ is the CO_2 emission factor of material i in the upstream production.

1. Integrated quantitative framework for urban GBIs' carbon reduction benefits.



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The calculation method for material transportation is shown in Eq. (2)[33]:

$$E_{CO_2}^t = \sum_i \left(Q_i^t \times EF_{CO_2,i}^t \right), \tag{2}$$

where t represents the transportation mode and i represents the type of fuel; $E_{CO_2}^t$ is the CO_2 emission in transportation mode i; Q_i^t is the consumption of a certain fuel in transportation mode i; and $EF_{CO_2,i}^t$ is the CO_2 emission factor of this fuel.

2.3.2 The C Stage

In the C stage, the primary carbon emissions of GBI arise from the construction processes of machinery and equipment, including diesel and electricity, and the calculation method is shown in Eq. (3)[33]:

$$E_{CO_2}^t = \sum_i EF_i \times X_i \times N_i \,, \tag{3}$$

where EF_i is the carbon emission factor of the mechanical equipment i; X_i is the unit workload of mechanical equipment i; and N_i is the number of mechanical equipment i.

2.3.3 The M & M Stage

The primary sources of carbon emissions during the M & M stage of urban GBIs typically fall into three categories: the electricity used by the irrigation system, the fuel consumed by the pruning machinery, and the emissions produced by irrigation water, fertilization, and pesticide use. This study adheres to the operational and maintenance guidelines set forth in the *Technical Guide for Sponge City Construction (Trial)*, taking into account Shanghai's geographical and climatic conditions.

(1) Carbon emissions from energy consumption in irrigation systems

The greenhouse gas emissions from electricity consumption of irrigation systems can be estimated based on the average level of electricity production and supply in a given region. The calculation method is shown in Eq. (4)[33]:

$$E_{CO_2}^{\theta} = Q^{\theta} \times EF_{CO_2}^{\theta} \,, \tag{4}$$

where $E_{CO_2}^{\theta}$ is the CO_2 emission caused by electricity consumption of the irrigation system; Q^{θ} is the total consumption of electricity in kWh; and $EF_{CO_2}^{\theta}$ is the CO_2 emission intensity of the electricity industry.

(2) Carbon emission of energy consumption in pruning process

The calculation method of carbon emissions caused by fuel consumption of the pruner is shown in Eq. (5)[33]:

$$E_{CO_2}^t = \sum_i \left(Q_i^t \times EF_{CO_2,i}^t \right), \tag{5}$$

where $E_{CO_2}^t$ is the CO_2 emission caused by fuel consumption of the pruner; Q_i^t is the total fuel consumption in the pruning process; and $EF_{CO_2,i}^t$ is the CO_2 emission factor of this fuel.

(3) Carbon emissions from fertilizers and pesticides

The CO_2 emissions of fertilizers and pesticides are the average CO_2 emissions produced during production, transportation, and use. The calculation method is shown in Eq. (6)[34]:

$$E_{CO_2}^t = \sum_i Q_i \times EF_i \times T_i \,, \tag{6}$$

where $E_{CO_2}^t$ is the CO_2 emission of fertilizer or pesticide application; Q_i is the amount of fertilizer applied per unit area; EF_i is the CO_2 emission factor of fertilizer or pesticide; and T_i is the number of times fertilizer or insecticide was used.

2.3.4 The WD Stage

Given that this study spans a 50-year accounting period, the disposal of urban BGIs is not considered temporarily, and the focus of the WD stage lies on the carbon emissions resulting from the recycling and treatment of waste associated with transporting green waste from GBIs and their subsequent resource disposal during their service life. Green waste primarily consists of organic materials generated from landscaping and gardening activities, including leaves and branches, grass clippings, plant debris, weeds, gardening residues, and landscaping leftovers. The calculation method for these emissions aligns with the approach outlined in Eq. (1).

This study intends to use the way of aerobic composting for the treatment of green waste. The specific calculation method is shown in Eq. (7)[35]:

$$E_{CO_2}^t = \sum_i EF_i \times T_i \,, \tag{7}$$

where $E_{CO_2}^t$ is the total CO_2 emission of greening waste; EF_i is the CO_2 emission factor of greening waste; and T_i is the i year(s).

2.4 Establishing a More Accurate GBIs' Vegetation Database

Taking into account Shanghai's specific geographical and climatic traits, alongside environmental considerations, the planting design was meticulously crafted[36]. This design integrated both ecological functionality and aesthetic value, leading to the selection of the most commonly used 36 species of landscape plants, including a mix of evergreen and deciduous trees, evergreen and deciduous shrubs, as well as herbs. Furthermore, a database detailing the carbon sequestration capacities of typical vegetation in Shanghai's GBIs is compiled in Table 2[36]~[42].

The methodology for calculating plant carbon sequestration within GBIs encompasses the sequestration from aboveground biomass, underground biomass, and litter, representing the entire carbon sequestration cycle of the plants. The total carbon storage of green spaces is the sum of carbon storage of each carbon pool[43] in the study area, and the calculation method is shown in Eq. (8):

$$C_{\text{tot}} = C_{\text{tree}} + C_{\text{shrub}} + C_{\text{grass}} + C_{\text{withered litter}}, \quad (8)$$

where C_{tot} is the total carbon storage of green space; C_{tree} is the carbon storage in the tree layer; C_{shrub} is the carbon storage of shrub layer; C_{grass} is the carbon storage of grass layer; and $C_{\text{withered litter}}$ is litter carbon storage in dead wood and leaves.

The carbon storage of the tree layer is the product of the sum of aboveground and underground biomass of each tree species and its carbon content rate. The calculation method is shown in Eq. (9)[44]:

$$C_{\text{tree}} = \sum_i^n \left(W_{\text{up},i} + W_{\text{down},i}\right) \times CF_i, \quad (9)$$

where $W_{\text{up},i}$ is the aboveground biomass of tree species in tree layer; $W_{\text{down},i}$ is the underground biomass of tree species in tree layer; n is the number of tree species in the tree layer; CF_i is the carbon content rate of tree species i (by using the reference value of carbon content rate of tree species or by actual measurement). Equation (9) is also suitable for the calculation of carbon storage of shrub and grass layers.

For the calculation of the carbon storage of withered litter[45], the biomass of litter layer is the sum of biomass of different types of litter layer, and the carbon storage of litter is determined by its

Table 2: Annual carbon sequestration capacity of different species

Species	Carbon sequestration	S1			S2			S3			Reference source
		SGS	GR	RG	SGS	GR	RG	SGS	GR	RG	
Acer palmatum Thunb.	5.39 kg/plant	—	—	—	9	—	5	—	—	—	[37]
Acer rubrum L.	48.46 kg/plant	—	—	—	19	—	9	—	90	—	[38]
Amygdalus persica L. var. *persica f. duplex* Rehd.	15.03 kg/plant	—	—	—	19	—	9	—	—	—	[36]
Aucuba japonica Variegata	126.53 kg/m^2	893.0	—	497.9	982.3	—	497.9	893	—	356.1	[36]
Buxus megistophylla Levl.	4.61 kg/m^2	6,027.5	—	3,360.8	736.9	3,198.6	3,734.2	6,027.5	2,516.2	2,403.5	[36]
Cerasus subhirtella (Miq.) Sok.	169.30 kg/plant	—	—	—	56	—	28	—	9	—	[36]
Cinnamomum camphora (L.) J. Presl	414.01 kg/plant	112	—	57	177	—	90	112	5	85	[39]
Fatsia japonica (Thunb.) Decne. et Planch	15.03 kg/m^2	446.5	—	248.9	245.6	—	—	—	—	178.0	[36]
Ginkgo biloba L.	130.21 kg/plant	19	—	9	19	—	9	19	—	14	[36]
Koelreuteria paniculata Laxm.	115.08 kg/plant	19	—	9	—	—	—	19	—	14	[40]

(Continued)

Table 2: Annual carbon sequestration capacity of different species (Continued)

Species	Carbon sequestration	S1			S2			S3			Reference source
		SGS	GR	RG	SGS	GR	RG	SGS	GR	RG	
Ligustrum japonicum 'Howardii'	220.85 kg/m^2	1,785.9	—	995.8	2,210.1	—	1,120.3	1,785.9	—	712.1	[36]
Ligustrum lucidum W. T. Aiton	169.30 kg/plant	31	—	16	—	—	—	31	14	24	[38]
Ligustrum vicaryi Rehder	24.06 kg/m^2	669.7	—	373.4	—	1,663.3	—	669.7	1,308.4	267.1	[36]
Loropetalum chinense var. rubrum Yieh	115.08 kg/m^2	1,116.2	—	622.4	—	—	—	1,116.2	—	445.1	[36]
Magnolia grandiflora Desr.	116.98 kg/plant	25	—	13	—	—	—	25	5	19	[36]
Malus halliana Koehne	46.16 kg/plant	167	—	85	4	—	—	167	71	25	[36]
Malus spectabilis (Aiton) Borkh.	24.06 kg/plant	—	—	—	19	—	14	—	—	—	[37]
Michelia alba DC.	4.61 kg/plant	—	—	—	—	—	—	—	5	—	[36]
Ophiopogogon japonicas (L. f.) Ker-Gawl.	0.43 kg/m^2	—	—	497.9	736.7	—	373.4	893.0	—	356.1	[39]
Osmanthus fragrans (Thunb.) Lour.	414.01 kg/plant	130	—	66	93	—	47	130	19	20	[36]
Photinia fraseri Dress	50.30 kg/m^2	5,134.5	—	2,862.9	6,384.6	—	3,226.3	5,134.5	—	2,047.4	[36]
Phyllostachys sulphurea (Carr.) A. 'Viridis'	130.21 kg/m^2	446.5	—	248.9	245.6	—	124.5	446.5	431.2	178.0	[36]
Pistacia chinensis Bunge	3.78 kg/plant	—	—	—	9	—	5	—	—	—	[36]
Pittosporum tobira (Thunb.) Ait.	66.78 kg/m^2	446.5	—	248.9	—	2,558.9	—	446.5	2,013.0	178.0	[36]
Platanus orientalis L.	87.36 kg/plant	372	—	189	—	—	—	372	—	283	[36]
Prunus cerasifera f. atropurpurea (Jacq.) Rehd.	116.98 kg/plant	143	—	72	84	—	42	143	42	22	[36]
Prunus mume	1.06 kg/plant	—	—	—	28	—	14	—	—	—	
Punica granatum L.	87.36 kg/plant	180	—	91	—	—	—	180	—	27	[36]
Rhododendron amesiae Rehder & E. H. Wilson	3.80 kg/m^2	446.5	—	—	736.7	1,279.4	124.5	446.5	1,006.5	178.0	[36]
Rhododendron dauricum L.	3.80 kg/m^2	4,018.3	—	2,240.5	4,911.3	—	2,489.5	4,018.3	—	1,602.3	[36]
Sapium sebiferum (L.) Roxb.	1,149.25 kg/plant	—	—	—	9	—	5	—	—	—	[36]

(Continued)

Table 2: Annual carbon sequestration capacity of different species (Continued)

Species	Carbon sequestration	S1			S2			S3			Reference source
		SGS	GR	RG	SGS	GR	RG	SGS	GR	RG	
Styphnolobium japonicum var. japonicum	126.53 kg/plant	19	—	9	—	—	—	19	—	14	[41]
Ulmus parvifolia Jacq.	74.90 kg/plant	—	—	—	9	—	5	—	—	—	[42]
Zelkova schneideriana Hand.-Mazz.	220.85 kg/plant	25	—	13	28	—	14	25	—	19	[36]
Lawn grass (as a mixture of *Sedum lineare* Thunb. and *Zoysia japonica* Steud.)	0.42 kg/m^2	7,441.3	21,323.9	3,372.0	7,069.2	8,529.6	3,583.4	3,720.7	4,072.9	1,886.0	[39]

NOTES

1. The carbon sequestration of the species without reference source was measured in this study.
2. As the carbon sequestration capacities of lawn grass species used in this study area—*Sedum lineare* Thunb. and *Zoysia japonica* Steud.—did not significantly vary, this study took the average carbon sequestration of two herb species.

biomass and carbon content rate. The calculation method is shown in Eq. (10)[44]:

$$C_{\text{withered litter}} = \sum_{i}^{n} A_i \times \overline{W_{\text{withered litter},i}} \times CF_{\text{withered litter}}, \quad (10)$$

where $C_{\text{withered litter}}$ is withered litter carbon storage; A_i is the area of the green space type i; $\overline{W_{\text{withered litter},i}}$ is the biomass of litter layer per unit area of the green space type i; and $CF_{\text{withered litter}}$ is the carbon content rate of litter layer.

3 Research Results

3.1 Life-Cycle Carbon Emission Analysis of GBIs Under Different Scenarios

The calculated carbon emission and carbon emission density of the GBIs within the study area at each stage of the whole life-cycle under the three scenarios are listed in Table 3.

Analyses show that under the three scenarios, the life-cycle carbon emissions of sunken green spaces are the largest while those of green roofs are the smallest. The average result of the three scenarios shows that the life-cycle carbon emissions of sunken green spaces are 1.68 times that of green roofs. In the P & T stage, rain gardens produce the most carbon emissions under each scenario, and their average carbon emissions under three scenarios are 137.6 and 3.4 times those of sunken green spaces and green roofs, respectively. A possible reason is that rain gardens have the most abundant types and quantities of vegetation, and their construction requires a large amount of building materials, increasing the associated road transportation and upstream production.

During the C stage, sunken green spaces produce the most carbon emissions under each scenario, and their average carbon emissions under three scenarios are 3.8 and 2.4 times those of green roofs and rain gardens, respectively. These discrepancies are mainly because sunken green spaces occupy the largest area and a great amount of mechanical equipment is required for foundation excavation and earthwork excavation/filling, which are associated with higher energy consumption and carbon emissions.

In the M & M stage, sunken green spaces produce the most carbon emissions under each scenario, and their average carbon emissions under three scenarios are 97% higher and 66% higher than those of rain gardens and green roofs, respectively. This is mainly because sunken green spaces cover the largest area and the plants in such spaces are of diverse species and great quantity. Therefore, fertilization and irrigation produce the highest carbon emissions.

In the WD stage, green roofs produce the lowest carbon emissions under each scenario, with average carbon emissions of only 60% and 86% of sunken green spaces and rain gardens, respectively. This is primarily because of the fewer types and numbers of green roofs, leading to the lowest amount of carbon

Table 3: Life-cycle carbon emission analysis of GBIs under different scenarios

Scenario	GBI type	P & T stage ($kg\ CO_2$)	C stage ($kg\ CO_2$)	M & M stage ($kg\ CO_2$)	WD stage ($kg\ CO_2$)	Total emission ($kg\ CO_2$)	Carbon emission density ($kg\ CO_2/m^2$)
S1	SGS	5,571.74	328,321.33	2,765,553.84	667,605.34	3,767,052.25	101.25
	GR	123,768.23	86,707.79	1,701,305.94	140,104.13	2,051,886.09	96.22
	RG	713,333.76	133,139.28	1,401,842.53	428,982.41	2,677,297.98	141.96
	Total	**842,673.73**	**548,168.39**	**5,868,702.32**	**667,605.34**	**8,496,236.32**	**109.78**
S2	SGS	4,862.33	328,321.33	2,816,286.19	826,139.17	3,975,609.01	106.85
	GR	249,275.81	86,707.79	1,701,305.94	336,269.35	2,373,558.89	111.31
	RG	714,348.81	134,803.52	1,427,558.45	418,761.58	2,695,472.36	142.92
	Total	**968,486.95**	**549,832.63**	**5,945,150.59**	**1,581,170.10**	**9,044,640.26**	**116.87**
S3	SGS	5,219.88	328,321.33	2,785,846.78	567,036.19	3,686,424.18	99.08
	GR	266,102.89	86,707.79	1,640,246.61	410,764.77	2,403,822.05	112.04
	RG	726,434.83	149,781.69	1,412,128.90	287,411.59	2,575,757.00	136.57
	Total	**997,757.59**	**564,810.80**	**5,838,222.29**	**1,265,212.55**	**8,666,003.23**	**111.79**

emissions generated during the corresponding transportation and resource treatment processes. The comparison results of the total carbon emissions of the three GBI types under the varied scenarios show that the life-cycle carbon emissions under S2 are the highest, i.e. 6% higher than those under S1 and 5% higher than those under S3.

The research also compared the three scenarios according to the carbon emission density of each GBI type. Under each scenario, the carbon emission density during the entire life cycle of rain gardens is the largest at approximately 34% higher than those of the other two GBI types on average. It also found that the total carbon emission density is the least in S1 and the largest in S2. However, the gap between the three scenarios is not significant.

3.2 Carbon Sequestration of Vegetation Within GBIs Under Different Scenarios

By comparing the total carbon sequestrations of sunken green spaces, green roofs, and rain gardens under the three scenarios (Table 4), it can be found that the carbon sequestration of S3 is the largest, 14% and 15% higher than those of S1 and S2, respectively.

3.3 Calibrated Carbon Sequestration of GBIs Based on LCA Approach

The study compared the carbon emissions and carbon sequestration of sunken green spaces, green roofs, and rain gardens, and the carbon sequestration/emission ratios (k, the higher the value of k, the stronger the carbon sequestration capacity of the GBI) under three scenarios (Table 5). The k-value during the entire life cycle of sunken green spaces is the highest under the three scenarios. Taking S3 as an example, the results show that the k-value during the entire life cycle of sunken green spaces is 1.6 times that of green roofs and 1.4 times that of rain gardens. It is mainly because fewer restrictions are placed on the choice of vegetation with high carbon sequestration capacity for sunken green spaces, and the construction of sunken green spaces is simpler than that of green roofs and rain gardens. In terms of green roofs, its k-value is 16.7 times that under S2 compared with S1. This finding is mainly because under S1, the vegetation is more homogeneous and does not have high carbon sequestration capacity, resulting in a smaller carbon sequestration, while the carbon emissions during the C stage are relatively high. When

Table 4: Carbon sequestration analysis of GBIs under different scenarios

Scenario	GBI type	Carbon sequestration (kg CO_2)
S1	SGS	15,408,000.00
	GR	383,488.00
	RG	15,408,000.00
	Total	**31,199,488.00**
S2	SGS	16,050,000.00
	GR	6,848,000.00
	RG	8,135,648.01
	Total	**31,033,648.01**
S3	SGS	18,703,600.00
	GR	7,276,000.00
	RG	9,480,741.81
	Total	**35,460,341.81**

the types of vegetation appropriately increase for green roofs, the carbon sequestration capacity of vegetation can increase significantly while the carbon emissions only increase slightly during the C stage, thereby leading to the increase of *k*-value.

Under S1, the total carbon emissions of sunken green spaces and rain gardens are both negative, which means that they exhibit a carbon sink effect during the life cycle; however, green roofs exhibit a carbon source effect during their life cycle. The vegetation used for roof greening in this scenario is relatively homogeneous and has low carbon sequestration capacity, thus the overall carbon reduction effect of green roofs is weak.

Under S2 and S3, the total carbon reduction emissions of sunken green spaces, green roofs, and rain gardens are all negative. That is, they all exhibit an effect of carbon reduction during the whole life cycle, and sunken green spaces have the best effect. S3 performs the greatest total carbon reduction benefit among the three GBI types.

Regarding the case studied in this research, the direct carbon emissions include the total carbon emissions in the C Stage, carbon emissions from energy consumption in irrigation systems and carbon emission of energy consumption in pruning process in the M & M Stage. The indirect carbon emissions include total carbon

Table 5: The life-cycle carbon sequestration/emission ratios of different GBIs under three scenarios

Scenario	GBI type	Total carbon sequestration (kg CO_2)	Total LCA carbon emission (kg CO_2)	*k*-value	Net benefit (kg CO_2)
S1	SGS	−15,408,000.00	3,767,052.25	4.93	−11,640,947.75
	GR	−383,488.00	2,051,886.09	0.20	1,668,398.09
	RG	−15,408,000.00	2,677,297.98	3.44	−12,730,702.02
	Total	**−31,199,488.00**	**8,496,236.32**	**3.23**	**−22,703,251.68**
S2	SGS	−16,050,000.00	3,975,609.01	5.05	−12,074,390.99
	GR	−6,848,000.00	2,373,558.89	3.34	−4,474,441.11
	RG	−8,135,648.01	2,695,472.36	3.55	−5,440,175.649
	Total	**−31,033,648.01**	**9,044,640.26**	**4.12**	**−21,989,007.74**
S3	SGS	−18,703,600.00	3,686,424.18	5.95	−15,017,175.82
	GR	−7,276,000.00	2,389,201.78	3.65	−4,886,798.23
	RG	−9,480,741.81	2,575,757.00	4.12	−6,904,984.81
	Total	**−35,460,341.81**	**8,651,382.96**	**4.77**	**−26,808,958.85**

emissions in the P & T stage, carbon emissions from fertilizers and pesticides in the M & M stage, and total carbon emissions in the WD stage. Under the three scenarios, direct carbon emissions account for more than 50% of the life-cycle carbon emissions of the GBIs, and the three types of GBIs show that the average indirect carbon emissions under all scenarios accounted for approximately 34% of the total carbon emissions, indicating that indirect carbon emissions are an important part of life-cycle carbon emissions and cannot be ignored (Table 6).

4 Conclusions and Policy Suggestions

This study establishes an integrated quantitative framework and methodology for GBIs' direct and indirect carbon reduction benefits in residential areas. It quantified the life-cycle carbon emissions of three typical urban GBIs—green roofs, sunken green spaces, and rain gardens. A meticulous selection process for plant species has led to diverse landscape combinations of trees, shrubs, and grasses, enabling to examine the carbon sequestration impact under various plant configurations. The results indicate that GBIs have a reducing effect on carbon emissions in residential areas.

Table 6: Direct and indirect carbon emissions of GBIs under three scenarios

Scenario	GBI type	Total direct carbon emissions (kg CO_2)	Total indirect carbon emissions (kg CO_2)	Proportion of direct carbon emission
S1	SGS	2,779,030.19	988,022.06	73.77%
	GR	1,562,457.62	489,428.47	76.15%
	RG	1,375,388.79	1,301,909.19	51.37%
	Total	**5,716,876.60**	**2,779,359.72**	**67.29%**
S2	SGS	2,810,084.73	1,165,524.28	70.68%
	GR	1,562,457.62	811,101.27	65.83%
	RG	1,392,794.39	1,302,677.97	51.67%
	Total	**5,765,336.74**	**3,279,303.52**	**63.74%**
S3	SGS	2,791,452.01	894,972.17	75.72%
	GR	1,516,892.30	872,309.48	63.49%
	RG	1,398,327.74	1,177,429.26	54.29%
	Total	**5,706,672.05**	**2,944,710.91**	**65.96%**

The findings show that the combination of high carbon sequestration vegetation with trees, shrubs, and grass yields the greatest carbon sequestration. Consequently, replacing vegetation with high carbon sequestration variants within GBIs can markedly amplify their building carbon reduction impact.

According to the Shanghai Master Plan 2017–2035[46], by 2035, the urban residential land area in Shanghai will be 830 km^2. According to the Statistical Bulletin of National Economic and Social Development for Shanghai in 2023[47], the forest coverage rate of Shanghai reached 18.8%. Based on these figures, a preliminary estimation suggests that the construction of GBIs in residential areas in Shanghai can achieve a carbon sink of approximately 540.54 million tCO_2eq per year. According to data released by the Shanghai Ecology and Environment Bureau, the annual carbon emissions in Shanghai are about 167 million tons. This level of carbon sequestration is equivalent to 32% of Shanghai's annual carbon emissions. It is evident that the construction of GBIs possesses significant potential for achieving urban carbon neutrality strategies.

To bolster the direct carbon sequestration capacity of GBIs and its carbon reduction effect on residential areas, we recommend two approaches: minimizing life-cycle carbon emissions of GBIs, and enhancing the carbon sequestration potential of the vegetation within GBIs. Several strategies are proposed to reduce their life-cycle carbon emissions across four key aspects as follows.

1) In the P & T stage, it is recommended to choose low fuel consumption-transportation vehicles, adopt electrified transportation, use alternative energy, and select the origin of materials in accordance with the principle of proximity[48]. All these measures can reduce the carbon emissions generated during transportation. In addition, it is recommended to select low-carbon building materials or materials produced with clean technology, which will contribute to a reduction in the carbon emissions generated by upstream production links.

2) In the C stage, appropriate construction plans should be developed in advance to reduce the additional carbon emissions caused by the repeated transportation of materials in the residential communities and the repeated operation of mechanical equipment used for construction.

3) In the M & M stage, pruning of vegetation contained in the GBIs must be reduced according to the actual situation and pesticide, insecticide, and chemical fertilizer use must also be

reduced. Plant resistance can be improved through scientific cultivation and maintenance methods[17]. In addition, sprinkler irrigation technology should be used rationally. All these measures can reduce carbon emissions while meeting the normal growth needs of vegetation.

4) In the WD stage, selecting suitable treatment plants located in proximity can reduce the carbon emissions generated during the transportation of waste. Moreover, scientific management and maintenance can be implemented on a daily basis to reduce the amount of green waste[49] in the process of green waste recycling.

To enhance the carbon sequestration capacity of vegetation within GBIs, we advocate for strategic vegetation selection and arrangement.

1) Vegetation selection: prioritize plants with robust carbon sequestration capabilities. Specifically, choose species native to the local region known for their high carbon sequestration efficiency. These plants are more likely to thrive, adapt to the local climate, and fulfill their growth requirements, exhibiting resilience to local environmental conditions. Such a strategic selection will not only improve the carbon sequestration of individual plants but also amplify the overall sequestration efficiency within GBIs.

2) Vegetation arrangement: implement thoughtful plant arrangements to boost carbon sequestration efficiency. Combinations such as tree-shrub-grass and shrub-grass are more effective than single-category arrangements like tree-only, shrub-only, or grass-only. This approach leverages the synergistic effects of diverse plant types to maximize carbon capture. The limitation of this study is that the selection of species combinations is specific to the Shanghai area and cannot be directly applied to other regions across the country. And in terms of vegetation selection, it is currently impossible to propose a fixed combination of trees, shrubs, and grasses. Future research can further improve these shortcomings with more target efforts.

Competing interests | The authors declare that they have no competing interests.

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城市绿蓝基础设施碳减排效益潜力研究

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摘要

在追求碳中和的过程中，城市绿蓝基础设施越来越受到关注，尤其是在居住区维度。在此背景下，本研究建立了一项综合性定量框架，并搭建了一个涵盖36种适用于上海当地环境植物的固碳量数据库，旨在利用生命周期评估方法精确校准不同情景下三种典型城市绿蓝基础设施（绿色屋顶、下沉式绿地和雨水花园）的固碳效益，从而评估直接和间接碳减排效益。研究结果表明，绿蓝基础设施可有效减少城市居住区的碳排放。且若将模拟结果置于城市尺度，初步估算结果表明，在上海居住区内建设绿蓝基础设施每年可实现约5.4054亿吨二氧化碳当量的碳汇潜力，这一固碳水平相当于上海年碳排放量的32%。本研究证明了绿蓝基础设施建设在提升碳减排效益和实现城市碳中和战略方面的巨大潜力。

关键词

绿蓝基础设施；生命周期评估；种植设计；绿蓝基础设施设计；碳减排效益；固碳；居住区

文章亮点

- 开发了一项综合性定量框架，用于评估城市绿蓝基础设施（GBI）的直接和间接碳减排效益
- 建立了一个涵盖36种适用于上海当地环境植物的固碳量数据库，并使用生命周期评估方法量化了GBI的固碳效益
- 初步估算结果表明，在上海居住区内建设绿蓝基础设施的固碳水平相当于上海年碳排放量的32%
- 提出乔木、灌木和草本的优化组合，以实现GBI的有效设计

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