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Original Article

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Quantitative evaluation and optimization of carbon sequestration in Chongqing's parks under the 'dual carbon' strategy

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Abstract

To quickly and efficiently evaluate the carbon sequestration benefits of urban parks, a quantitative evaluation method for carbon sequestration is designed taking sponge city parks as an example. The correlation between the average diameter at breast height of plants and the net primary productivity of vegetation was the strongest. Through optimized design, urban parks can better integrate the positive and negative benefits of sponge facilities, effectively enhancing their carbon sink capacity. At the same time, by promoting and applying the construction concepts and technical means of sponge-type parks, the study is expected to form more green spaces within the city.

Keywords: carbon fixation; carbon sequestration quantification; city park; dual carbon goal

1 Introduction

The dual carbon goal refers to a carbon reduction goal that combines the 'peak carbon emissions' and 'carbon neutrality'. 'Peak carbon emissions' refer to the gradual decrease in carbon emissions before a certain time point, with a turning point from increase to decrease, which is called carbon peak [1]. 'Carbon neutrality' refers to achieving a balance between carbon emissions and absorption. The dual carbon goal has profound impacts on the economy, environment, and society, which has established a green and sustainable economic system, and promoted the upgrading and transformation of social industrial structure. In addition, the dual carbon goal is an important means to improve urban environmental quality and protect the ecosystem. 'Dual carbon' has become an important strategic means for developing low-carbon cities [2].

Urban park greening is a crucial carrier for absorbing carbon dioxide (CO_2) and increasing green carbon sequestration (CO_2Seq), which is of great significance for mitigating and adapting to climate change. Sponge-type parks are urban parks that incorporate the concept of 'sponge cities' into urban park renovation projects and strengthen the function of sponge bodies. The construction of sponge-type parks is an important measure to implement ecological civilization construction and promote urban green transformation and development. It goes hand in hand with the 'dual carbon' strategic goal in both directions [3]. Therefore, promoting the construction of sponge parks has become an effective measure and path to promote carbon peak and carbon neutrality goals. Sponge-type parks have rich carbon source and CO_2Seq benefits. Carbon elements exist in different forms in nature. The process, activity, or mechanism of carbon storage releasing CO_2 into the atmosphere is the carbon source. CO_2Seq refers to the process, activity, or mechanism of removing CO_2 from the atmosphere [4]. However, in the construction of sponge-type parks, in order to fit the concept of 'sponge' and meet the needs of runoff reduction and purification, the configuration of green space plants is limited by bioretention facilities, grass-planting ditches, and other low-impact development (LID) facilities. The plant configuration directly affects the carbon sink efficiency of the facility. Moreover, the operation and maintenance of LID facilities may partially offset the contribution of LID facilities to carbon sinks. Moreover, most of the existing studies focus on the measurement of carbon sinks at the macro level, but lack a systematic calculation of the carbon sink efficiency of urban parks. Therefore, it is necessary to carry out a comprehensive study on the quantification of carbon sinks in order to understand the value of sponge city parks in promoting the development of low-carbon cities [5].

In order to explore the mechanism of carbon sink efficiency of sponge-type park construction and to develop a carbon sink efficiency remittance method applicable to sponge-type

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parks, so as to more accurately assess the carbon emission reduction and carbon sequestration capacity of the parks, a method for rapid quantification of CO_2Seq in sponge city parks is innovatively designed, taking sponge city parks as an example and combining existing CO_2Seq theory knowledge. Sensitivity analysis of CO_2Seq factors and impact analysis of LID facilities are conducted. This study is expected to provide reference for the green space planning and construction of urban sponge parks, promoting the CO_2Seq benefits.

The research mainly consists of four parts. The first part mainly elaborates on the current research status of green space CO_2Seq function evaluation and outlines the progress and shortcomings of the research. The second part designs a CO_2Seq quantification method for urban sponge parks. The third part implements specific quantitative analysis of CO_2Seq. The fourth part summarizes the research results.

2 Related works

Supporting the dual carbon goal and developing green CO_2Seq is a hot topic for all sectors of society. In order to seize the opportunity of the 'dual carbon' strategy, domestic and foreign scholars have carried out a series of studies on CO_2Seq quantification and evaluation. Different components of coastal landscapes have different responses to sea level rise and coastal erosion. It is hard to predict the comprehensive CO_2Seq response of coastal ecosystems. Valentine *et al.* [6] combined a spatial explicit geomorphological model and point-based carbon accumulation model to conduct CO_2Seq analysis of coastal ecosystems. The experimental results indicated that when the sea level rise rate reached a moderate level, the CO_2Seq response of landscape connectivity, *in situ* carbon accumulation rate, and landscape scale coastal carbon storage reached its peak. Climate change strengthened the connectivity of coastal ecosystems [6]. Expanding agricultural scale will increase agricultural carbon emissions. Li *et al.* [7] summarized the agricultural technology development, agricultural carbon emissions, and CO_2Seq. The fixed effects model was used to estimate the agricultural technology, and the impact of the constituent factors of technological development on agricultural carbon emissions and CO_2Seq was analyzed. Agricultural CO_2Seq was roughly 10 times that of agricultural carbon emissions, and the impact of agricultural technology level on CO_2Seq was not significant [7]. Singkran [8] analyzed the CO_2Seq capacity of 25 public parks in Bangkok, Thailand. The CO_2 absorption in all parks accounted for 83.6% of greenhouse gas absorption in urban green spaces. The tree group, species, diversity, density, and diameter significantly affected the above-ground CO_2Seq and CO_2 absorption in the park. This study helped to determine reasonable park management standards and improve the above-ground CO_2Seq rate of parks [8].

Urban CO_2Seq quantification often overlooks natural CO_2Seq space and soil. Fan *et al.* [9] constructed a measurement system for urban CO_2Seq capacity to evaluate the contribution of natural CO_2Seq to urban CO_2Seq, taking Hangzhou, China, as the research object. The research results indicated that the CO_2Seq capacity of soil and small green spaces had crucial impacts on urban CO_2Seq, while the contribution of natural CO_2Seq to urban space was limited [9]. The rich CO_2Seq capacity of ecological protected areas is of great significance for improving plant functions. Ali *et al.* [10] evaluated the CO_2Seq, diversity, and abundance of woody plants in the Margara Mountains National Park in Pakistan through quantitative and functional ecology. The CO_2Seq rate of white acacia was the highest, reaching 2620.75 pounds per year. The CO_2Seq rate of African loofah was only 1.81 pounds per year. The diameter at breast height and crown of plants had crucial impacts on CO_2Seq [10]. The quantification of carbon neutrality and the calculation of spatial service scope are of great significance for carbon neutrality spatial planning and carbon trading markets. Ma *et al.* [11] quantified CO_2Seq in the Qinling Mountains region of China using an intelligent urban ecosystem. With the help of land use simulation models and net present value models, the spatial distribution of CO_2Seq was simulated. The carbon in the Qinling region increased, and the service scope gradually expanded [11]. Xu *et al.* [12] estimated the net primary production value of five different cities in China using a process remote sensing model based on satellite imagery, meteorological data, and vegetation type data. The net ecosystem productivity was evaluated. The results indicated that Beijing, China, had the highest net primary production value and vegetation CO_2Seq capacity. The net ecosystem productivity in most areas showed obvious spatial agglomeration characteristics [12]. Forests are an important component of balancing the carbon balance of terrestrial ecosystems. Lü *et al.*[13] conducted a research on the carbon balance response of forests in Southwest China using a carbon balance model of forest ecosystems in China. The experimental results showed that the total primary productivity and net primary productivity (NPP) of forest ecosystems were both on the rise. The CO_2Seq potential in the northwest and central regions of Yunnan exceeded other regions. This study is expected to scientifically guide forest management strategies [13].

In summary, there have been many studies and applications related to the quantification and evaluation of green space CO_2Seq, covering a wide range of carbon sink studies from coastal ecosystems to urban green spaces, agriculture, forests, etc.; it shows the breadth and diversity of carbon sink studies under the dual carbon goal. However, most of the studies focus on the carbon sink measurement at the macro level and lack in-depth analysis at the micro level; they lack in-depth exploration of the carbon sink mechanism of sponge-type urban parks, especially in terms of the influence of LID facilities on the plant configuration and carbon sink efficiency. At the same time, there is a lack of carbon sink efficiency calculation methods for sponge-type urban parks, which makes it impossible to accurately assess their carbon emission reduction and carbon absorption capacity. Therefore, this study conducts a quantitative evaluation and optimization study on carbon sequestration based on urban sponge parks.

3 Construction of quantitative evaluation method and optimization strategy design for carbon sequestration in Chongqing parks

In order to achieve optimal CO_2Seq in urban parks and explore the key processes of CO_2Seq in parks, a quantitative evaluation study of CO_2Seq in sponge parks is conducted.

3.1 Theoretical analysis of carbon sequestration in sponge parks

Sponge city is an urban stormwater management concept that helps cities adapt to environmental changes and deal with

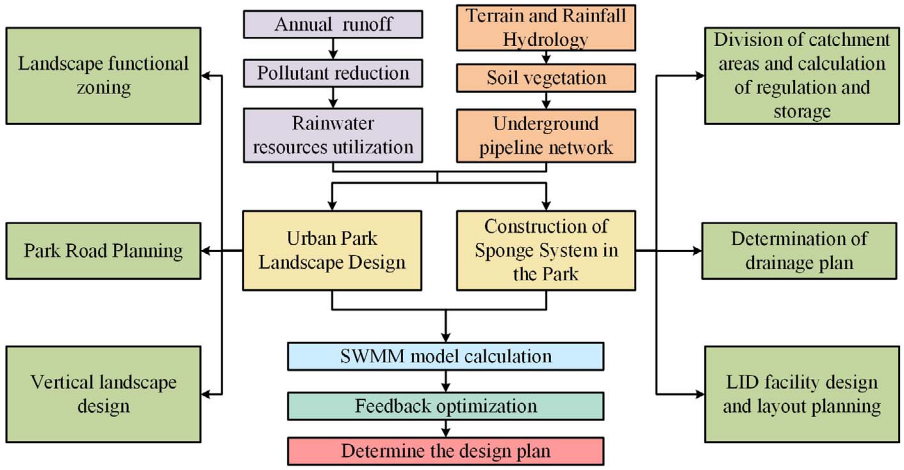

Figure 1. Schematic diagram of the design process for sponge city park.

various natural disasters caused by rainwater through urban terrain, various building facilities, and technology.

LID is a development model that manages stormwater through decentralized, small-scale facilities that emphasize controlling stormwater runoff at the source and reducing pressure on urban drainage systems while promoting natural accumulation, infiltration, and purification of stormwater. LID is crucial in the construction process of sponge cities, as it can integrate cities and nature. Common LIDs include green roofs, permeable paving, bioretention facilities, infiltration ponds, infiltration wells, wet ponds, sunken green spaces, and other types of facilities.

The sponge park is to apply the sponge city concept to park construction, and realize the natural accumulation, natural infiltration, and natural purification of rainwater by setting up rainwater collection devices, adopting permeable materials and constructing rain gardens and other measures [14].

A carbon sink is a process, activity, or mechanism that removes carbon dioxide from the air, such as the absorption and storage of carbon dioxide by ecosystems such as forests, grasslands, and soils through photosynthesis. Carbon sinks reduce the concentration of carbon dioxide in the atmosphere and mitigate the greenhouse effect.

Carbon sources are processes, activities, or mechanisms that release carbon dioxide into the atmosphere, such as fossil fuel combustion and deforestation. Carbon sources increase the concentration of carbon dioxide in the atmosphere and exacerbate the greenhouse effect.

Low-carbon landscape refers to a landscape that reduces carbon dioxide emissions and increases carbon sinks by adopting environmentally friendly materials, optimizing plant configurations, and reducing energy consumption and other measures in the process of landscape design and construction.

Life cycle assessment (LCA) theory is a systematic approach to assessing the environmental impact of a product, service, or activity throughout its life cycle. This includes all stages from the acquisition, production, and use of raw materials to their final disposal.

In summary, the theories involved in the study will be verified in the analysis of the amount of carbon sink contribution and elemental sensitivity and the analysis of the impact of LID facilities on the function of carbon sinks.

3.2 Overview of the study area

Sponge city park includes both artificial and natural landscapes. The research is conducted to determine park design elements based on the classification of natural and artificial elements. The natural elements include soil, terrain, plants, and water bodies. Artificial elements include hard paving, structures, and crowd activities. The design process of sponge city park proposed through literature and data review is shown in Fig. 1.

As shown in Fig. 1, the study is to meet the basic functions of urban parks and control rainwater runoff. According to the general situation of the city park, combined with the landscape design and sponge system construction, the sponge city park design is completed with the help of the stormwater management model. The study takes Chongqing, China, as the object of CO_2Seq analysis for urban parks. Chongqing is located in the southwestern inland region of China and the upper reaches of the Yangtze River, with a planned urban area of 82 400 km^2, a permanent population of 32.133 million, and an urbanization rate of 70.96%. Chongqing belongs to a subtropical humid monsoon climate with abundant rainfall, with annual precipitation of 1000 to 1400 mm, mainly concentrated in summer. The 14th Five Year Plan for Sponge City Construction in Chongqing (2021–2025) outlines the development blueprint for Chongqing sponge city. Chongqing is continuously promoting the construction of sponge cities with the principle of 'ecological priority, planning guidance, and comprehensive promotion'. The sponge city concept is actively applied in park renovation projects. The study takes the Longmen Park in the Jiulongpo area of Chongqing as the object of CO_2Seq analysis. The actual park scenery is shown in Fig. 2.

As shown in Fig. 2, Longmen Park is located on the west side of Huayan Lake in Chongqing, adjacent to Huayan Tourist Scenic Area to the east, with a total area of approximately 3.98 hectares. The positioning of this park is to meet the leisure and entertainment needs of urban residents. Then according to the sponge city planning indicators, natural terrain elevation differences and LID facilities such as stepped rainwater gardens, grassy ditches, and permeable paving are used to construct the sponge park. The rainwater treatment mechanism is shown in Fig. 3.

Figure 2. Real view of Longmen park.

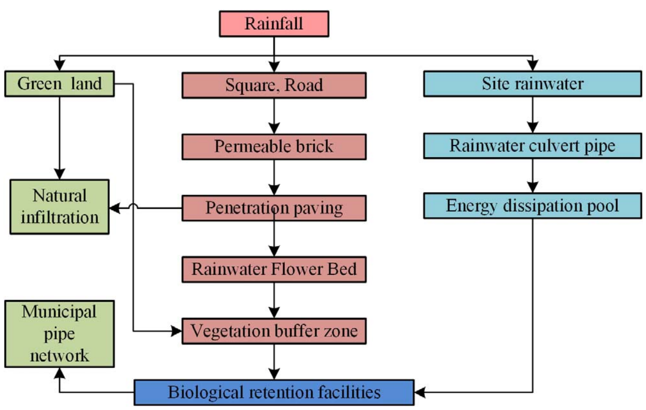

Figure 3. Schematic diagram of rainwater treatment mechanism in Longmen park.

As shown in Fig. 3, Longmen Park utilizes LID facilities to collect excess rainwater and directs it into the municipal rainwater pipeline network. The study draws on the theory of LCA as the basic theory of park construction cycle to analyze the carbon source and CO_2Seq process of urban parks. According to the LCA, the CO_2Seq assessment objectives for urban parks are determined, and the scope of different stages of the life cycle is delineated. Finally, the life cycle inventory is sorted out and the impact assessment is determined.

The sources of CO_2Seq in urban parks include plants and soil. Plants absorb CO_2 through the photosynthesis, which is the main contributor to the CO_2Seq of park green spaces. Plant CO_2Seq is influenced by species, age, growth status, community characteristics, and habitat factors, and requires multiple understandings of plant CO_2Seq. At the same time, full attention should be paid to the CO_2Seq process of soil microorganisms. Urban carbon emissions mainly come from urban life, agriculture, industrial production, and various energy activities. The CO_2Seq analysis of sponge city parks should fully consider various sources of carbon emissions. Therefore, when analyzing the CO_2Seq function of sponge city park, three processes are mainly considered, namely CO_2Seq by plants and soil, carbon emissions, and carbon reduction.

3.3 Construction of quantitative evaluation method for park carbon sequestration

On the basis of the theoretical analysis of CO_2Seq in sponge-shaped parks and the overview of Longmen Park in Chongqing, the scope of CO_2Seq analysis in Chongqing Park is divided into four stages: construction material production, park construction, urban park operation, and equipment demolition. The scope of carbon source and CO_2Seq is shown in Fig. 4.

As shown in Fig. 4, the entire park construction lifecycle continuously generates carbon emissions and plays a CO_2Seq role. The urban park operation phase will generate the maximum CO_2Seq benefits. Therefore, the study chooses the operation phase after the park construction is completed as the CO_2Seq quantification cycle. Quantitative analysis of CO_2Seq requires first identifying the CO_2Seq and emission processes of sponge city parks. Based on the operational characteristics of a sponge city park, the carbon source carbon emission process is determined, excluding carbon emissions that are not directly contributed to landscaping, carbon emissions from nonrepresentative facilities in the park, and carbon emissions from local engineering changes during the park's operation phase. Finally, based on literature and data, carbon sources with accessibility and recognizability are identified. Then, the quantitative analysis needs to clarify the CO_2Seq, emission reduction, and carbon emission process of the park. The CO_2Seq quantitative indicators for sponge-type parks determined through research are displayed in Table 1.

As shown in Table 1, for plant CO_2Seq, the study comprehensively considers the CO_2Seq efficiency of trees, shrubs, and ground cover plants. For soil CO_2Seq, only the

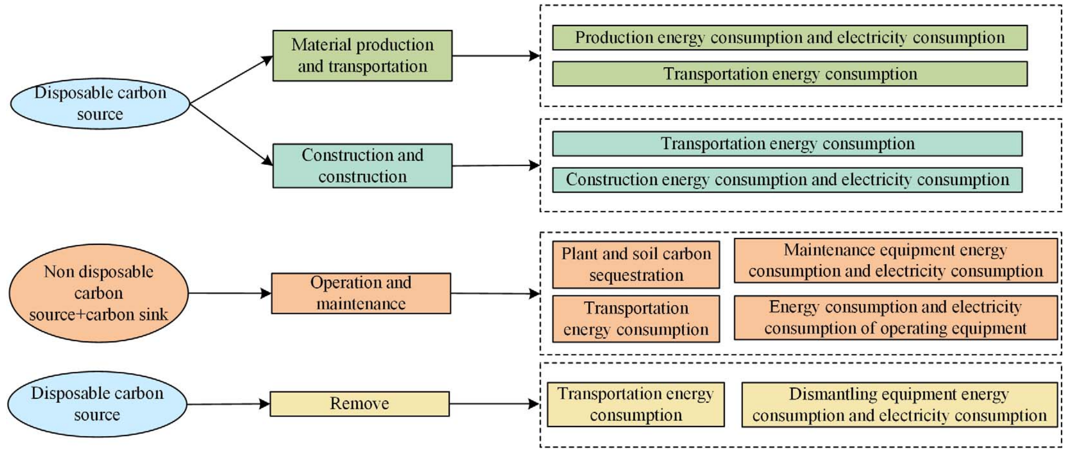

Figure 4. Schematic diagram of the scope division of carbon source and sequestration research in the park.

Table 1. Quantitative indicators of carbon sequestration in sponge parks

Dimension	Process	Calculate boundaries	Calculation indicators
Direct carbon sequestration	Plant carbon sequestration	Trees, shrubs, and ground cover plants	Plant quantity and unit amount of plant carbon sequestration
	Soil carbon sequestration	Organic carbon sequestration	Organic carbon density and soil area
Carbon reduction	Rainwater recycling	Facility collection of rainwater	Collect rainwater volume
	Weakening of rainwater runoff	LID reduction effect	Reduce the total amount
	LID facility rainwater purification	LID purification effect	Total purification amount
Carbon emission	Pollutant degradation	The degradation of chemical oxygen demand by LID	Total degradation amount
	Lighting	Street lights and night scene lighting	Electricity consumption
	Maintenance management	Irrigation, pruning, fertilization, and permeable paving	Equipment and material consumption

organic CO_2Seq generated by organic matter decomposition is considered. Sponge-type parks have achieved effective recycling of rainwater resources, reduced energy consumption of facilities such as water intake, storage, and supply, and achieved carbon reduction. At the same time, sponge-shaped parks effectively weaken the rainwater runoff and slow down the pressure of rainwater transportation in municipal pipelines. Various LID facilities have achieved rainwater purification. Carbon reduction has been achieved through park and green space purification [15, 16]. The carbon emission process involved in sponge parks includes pollutant degradation, lighting, and maintenance management. The LID facility removes greenhouse gases during the adsorption and degradation process of rainwater pollutants. The study only considers the degradation of chemical oxygen demand by LID facilities. Lighting carbon emissions include carbon emissions from park streetlights and night scenes. The energy consumption was caused by green space irrigation, pruning, fertilization, and permeable paving during the operation, maintenance, and management process of the park [17]. Based on the park construction project catalog, materials, on-site research and measurement, and park operation and management data, the CO_2Seq and carbon reduction emissions are determined. From the 2006 IPCC National Greenhouse Gas Inventory Guidelines, the carbon emission (CO_2eq) coefficient is determined. The study conducts CO_2Seq calculations based on field research, observing and recording the distribution, growth environment, diameter at breast height, height, and crown width of plant communities. The i-tree software and LI-6400 photosynthesis analyzer are used to assist in measuring plant photosynthetic rate and tree CO_2Seq. The LA-S portable leaf area analyzer is used for plant leaf area measurement [18]. For the soil organic carbon content, the ring knife method is used for on-site soil sampling to determine soil bulk density. The potassium dichromate volumetric method and external heating method are used for soil organic matter determination.

The calculation process of the total annual CO_2Seq CS during the operation stage of the park is shown in equation (1). The CO_2Seq comparison can be completed by converting the annual CO_2Seq CS into the annual CO_2Seq per unit area.

$$CS = CS_a + CS_b + CS_c + CS_d + CS_e - CE_a - CE_b - CE_c \quad (1)$$

In equation (1), CS_a and CS_b respectively represent the total CO_2Seq of plants and soil (kgCO_2eq/a). CS_c, CS_d, and CS_e respectively represent the annual carbon reduction emissions (kgCO_2eq/a) of rainwater utilization, runoff reduction, and rainwater purification. CE_a, CE_b, and CE_c respectively represent carbon emissions (kgCO_2eq/a) generated by pollutant degradation, lighting, and maintenance management. The total annual CO_2Seq of green plants and soil in the park is shown in equation (2).

$$\begin{cases} CS_a = \sum_{i=1}^{n} M_{ai} \times N_i \\ CS_b = \delta_{DSOC} \times S_b \times 1000 \end{cases} \quad (2)$$

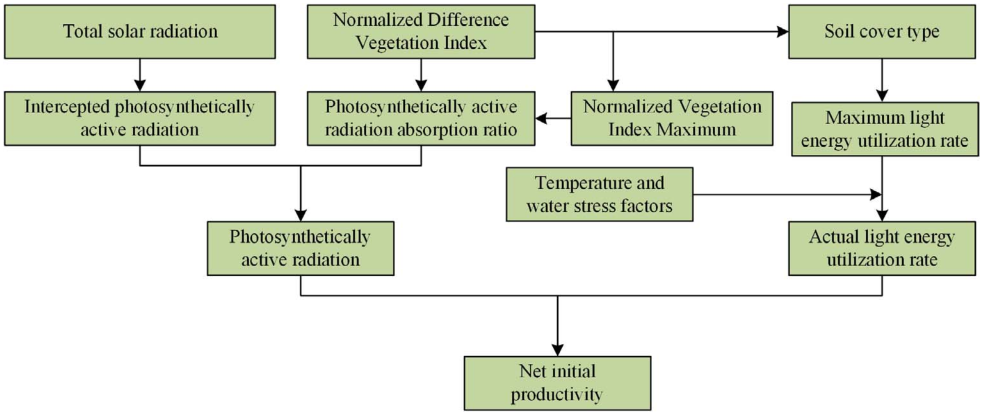

Figure 5. Frame diagram of vegetation net primary productivity estimation model.

In equation (2), M_{ai} represents the annual CO_2Seq of a single plant. i represents plant species. N represents the number of plants. δ_{DSOC} represents the difference in soil organic carbon density (t/hm^2). δ_{DSOC} represents the soil coverage area within the park (hm^2). The calculation process for different emission reductions is shown in equation (3).

$$\begin{cases} CS_c = \sum_{k=1}^{n} M_{ck} \times QE \times EF_{ec} \\ CS_d = \sum_{p=1}^{n} M_{dp} \times QE_d \times EF_{ec} \\ CS_e = \sum_{p=1}^{n} M_{ep} \times EF_p \end{cases} \quad (3)$$

In equation (3), k represents the type of LID facility. p represents different catchment zones. M_{ck} and M_{dk} respectively represent the amount of collected rainwater and the weakened peak runoff of rainwater (m^3/a). EF_p represents the amount of runoff reduction. EF_p and M_{dk} represent the carbon emission coefficients (kgCO_2eq/kwh) for rainwater purification and electricity consumption, respectively. QE and QE_d represent the electricity consumption (kwh/m^3) for treating tap water and rainwater. The calculation process of carbon emissions is shown in equation (4).

$$\begin{cases} CE_a = \sum_{p=1}^{n} M_{codp} \times B_o \times MCF_j \times GWP_{CH_4} \\ CE_b = \sum_{p=1}^{n} Q_{bp} \times EF_{ec} \\ CE_c = CE_{ca} + CE_{cb} + CE_c + CE_{cd} + CE_{ce} \end{cases} \quad (4)$$

In equation (4), M_{codp} represents the chemical oxygen demand for degradation treatment in the catchment zone. B_o represents the methane emission coefficient. MCF_j represents the corrected value of methane emission coefficient. GWP_{CH_4} represents the potential value of global warming. Q_{bp} represents the annual power consumption (kWh/a) of the p-th lighting facility. CE_{ca}, CE_{cb}, CE_c, CE_{cd}, and CE_{ce} respectively represent the annual carbon emissions generated by irrigation, pruning, fertilization, pesticide application, and permeable paving processes in park green spaces, which are related to the consumption generated by material transportation and treatment processes.

Finally, the study uses the Carnegie–Ames–Stanford Approach model to analyze the framework of the NPP estimation model for vegetation, as shown in Fig. 5 [19, 20].

As shown in Fig. 5, the core of the NPP estimation process is to analyze the absorbed photosynthetic effective radiation $APAR\,(x,t)$ of plants and the actual light energy utilization rate $\varepsilon\,(x,t)$. The calculation process is displayed in equation (5).

$$NPP\,(x,t) = APAR\,(x,t) \times \varepsilon\,(x,t) \quad (5)$$

In equation (5), $APAR\,(x,t)$ is related to the absorption ratio of total solar radiation to effective radiation. The calculation process of $\varepsilon\,(x,t)$ is shown in equation (6).

$$\varepsilon\,(x,t) = T_{\varepsilon 1}\,(x,t) \times T_{\varepsilon 2}\,(x,t) \times W_{\varepsilon}\,(x,t) \times \varepsilon_{\max} \quad (6)$$

In equation (6), $T_{\varepsilon 1}\,(x,t)$ and $T_{\varepsilon 2}\,(x,t)$ signify temperature stress factors. $W_{\varepsilon}\,(x,t)$ signifies a water stress factor. $\varepsilon_{\max}$ signifies the maximum light energy utilization rate.

4 Analysis of carbon sequestration function in Chongqing parks

After completing the data collection and preprocessing of CO_2Seq quantification for sponge parks in Chongqing, the study conducts CO_2Seq quantification.

4.1 Carbon sequestration contribution and factor sensitivity analysis

On the basis of the equations for CO_2Seq, emission reduction, and carbon emissions calculation, the calculated values of carbon sources and sequestrations in Longmen Park are determined. The statistical results are shown in Fig. 6; as displayed in Fig. 6a, the total annual CO_2Seq of plants was 81 316.36 kgCO_2eq/a, and the annual soil CO_2Seq was 3243.59 kgCO_2eq/a. The carbon reduction rates for rainwater utilization, runoff reduction, and rainwater purification were 0, 493.61 kgCO_2eq/a and 6394.16 kgCO_2eq/a, respectively. The annual carbon emissions of pollutant degradation, lighting facilities, and maintenance management were 486.16 kgCO_2eq/a, 6034.19 kgCO_2eq/a, and 29 431.16 kgCO_2eq/a, respectively. The total annual CO_2Seq of the park was 55 496.21 kgCO_2eq/a, showing an overall CO_2Seq effect. In Fig. 6b, direct CO_2Seq contributed the most to park CO_2Seq, and the contribution of plants to CO_2Seq far exceeded that of soil. The contribution of rainwater utilization, purification, and weakening to CO_2Seq was relatively

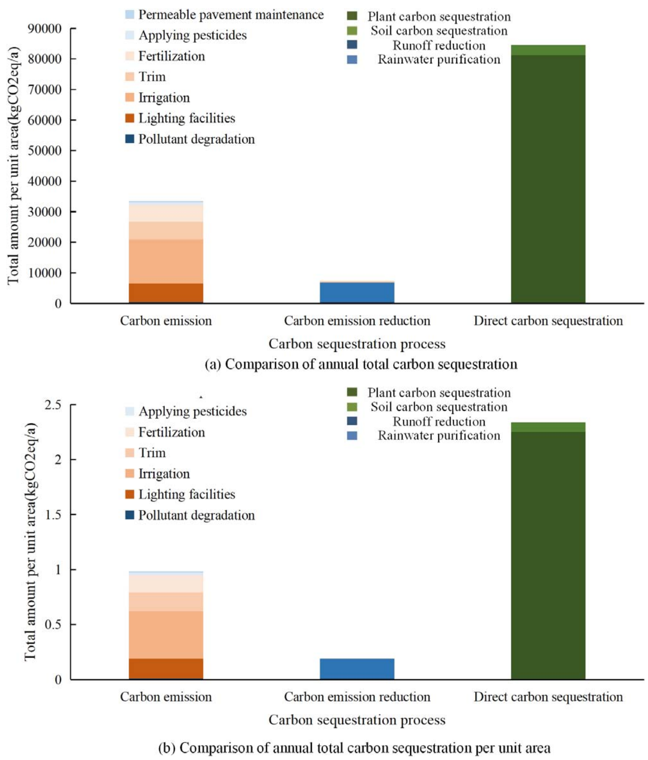

Figure 6. Analysis chart of statistical results of carbon sequestration process of each carbon source.

small, accounting for 10.95%. Among them, the contribution of rainwater purification through LID facilities to CO_2Seq reached 90.28%. In the analysis of carbon source and carbon emissions, the irrigation of plant green spaces in parks generated the largest carbon emissions. The irrigation process in parks is controlled to reduce the total carbon emissions.

The sensitivity analysis results of park CO_2Seq to different factors are shown in Table 2. As shown in Table 2, there were significant differences in the sensitivity of various factors to CO_2Seq. The sensitivity of plant CO_2Seq function to diameter at breast height was as high as 89.67% and 78.94%, respectively. The sensitivity of pruning method was the lowest, only 4.91%. It is consistent with the analysis results in Fig. 6. Changing the plant CO_2Seq process has the greatest impact on the park's CO_2Seq. During the research and actual measurement process, trees and shrubs had the highest CO_2Seq capacity. Based on sensitivity analysis results, high CO_2Seq plants could be used more frequently in park construction. In addition, the sensitivity of canopy closure to evergreen leaf ratio was 7.31% and 6.36%, respectively. Changing the crown width of trees and increasing the number of evergreen plants can optimize the CO_2Seq effect of the park. The sensitivity of irrigation methods was 21.05%, indicating that increasing artificial irrigation can improve park CO_2Seq.

The analysis results of the impact of different plant characteristics on NPP are shown in Fig. 7. In Fig. 7, NPP was positively correlated with characteristic changes within a crown width of 5 m, a tree height of 10 m, and a diameter at breast height of 10 m. The growth rate of NPP was relatively fast. Within this range, the impact of vegetation height, crown width, and diameter at breast height on NPP varied linearly. Comparative analysis shows that the correlation between plant average diameter at breast height and NPP is the strongest.

4.2 The impact of LID facilities on carbon sequestration function

The study conducts a quantitative comparative analysis of CO_2Seq between Longmen Park and conventional urban parks without LID facilities, assuming that nonsponge parks have the same elements of CO_2Seq in nonsponge functions as Longmen Park. The quantification results of carbon sources and sequestrations for two types of parks are shown in Table 3. In Table 3, the CO_2Seq and irrigation carbon emissions of non–sponge-type parks were 90 465.94 and 23 923.95 kgCO_2eq/a, respectively. Compared with sponge-type parks, the CO_2Seq and irrigation carbon emissions decreased by 10.11% and 38.63%, respectively. LID affects the CO_2Seq ability of plants, which is due to the lack of tall trees in sponge parks, mainly shrubs and ground cover plants. However, sponge parks have significantly improved carbon emissions compared with nonsponge parks, with a maximum increase of 430.22%. Compared with nonsponge parks, sponge parks have stronger rainwater storage capacity. External organic matter is more easily preserved in the soil after decomposition, resulting in a 20.62% increase in soil CO_2Seq. Overall, sponge parks have stronger CO_2Seq benefits, and LID facilities have more active impacts on CO_2Seq functions.

The analysis results of the impact mechanism of soil CO_2Seq in the LID facility area are shown in Fig. 8. Among them, the biological retention pool 2, grass planting ditch, and habitat island area are the structures of ground cover plants. The other areas have a composite vegetation structure. As shown in Fig. 8a, compared with ground cover plants, the composite vegetation structure composed of trees, shrubs, and grass plants had a higher soil organic carbon content, with the highest being 17.64 g/kg. Composite vegetation has a stronger CO_2Seq effect and enhances soil organic matter. However, the LID facility areas are mostly dominated by ground cover plants with low organic carbon content, which limits the growth of soil CO_2Seq benefits in sponge parks. In addition, the composite vegetation structure has a higher organic carbon density, which is consistent with the difference in organic carbon content. As shown in Fig. 8b, the soil bulk density of ground cover plants was higher than that of composite vegetation structures, but the overall difference was not significant.

Further analysis of the CO_2Seq contradiction caused by the LID facility area is shown in Fig. 9. As shown in Fig. 9a, the area without LID facilities in the sponge park had the highest annual total CO_2Seq, reaching 53 134.61 kgCO_2eq/a. The maximum annual CO_2Seq in the LID facility area was only 16 431.46 kgCO_2eq/a, located in the vegetation buffer zone. Due to differences in the area and vegetation structure of LID facility areas, there are differences in the CO_2Seq benefits of plants in different LID facility areas. Therefore, utilizing LID facilities to maximize plant CO_2Seq benefits may inhibit the carbon reduction benefits of LID facilities. The optimization of park CO_2Seq benefits needs to comprehensively consider the impact of LID facilities on plant CO_2Seq and carbon reduction. Figure 9b shows the runoff reduction and annual CO_2Seq per unit area of plants in different catchment zones. According to the two CO_2Seq benefits of CO_2Seq and emission reduction, different LID facility areas in Longmen Park

Table 2. Sensitivity analysis of different influencing factors on carbon sequestration

Dimension	Influence factor	Conditions that need to be changed	Management elements	Absolute sensitivity value
Direct carbon sequestration	Plant carbon sequestration function	Plant species number or crown width of trees	Plant	89.67%
	Diameter at breast height			78.94%
	Canopy closure degree	Number of evergreen and green leafed tree species		7.31%
	Evergreen leaf to leaf ratio	Irrigation pathways		6.36%
Carbon emission	Irrigation method	Types of lighting facilities	Small item facilities	21.05%
	Energy efficiency of lighting	Green space elevation		13.76%
	Green underground concavity	Pruning pathway	Terrain	15.43%
	Trimming method	Conditions that need to be changed	Equipment	4.91%

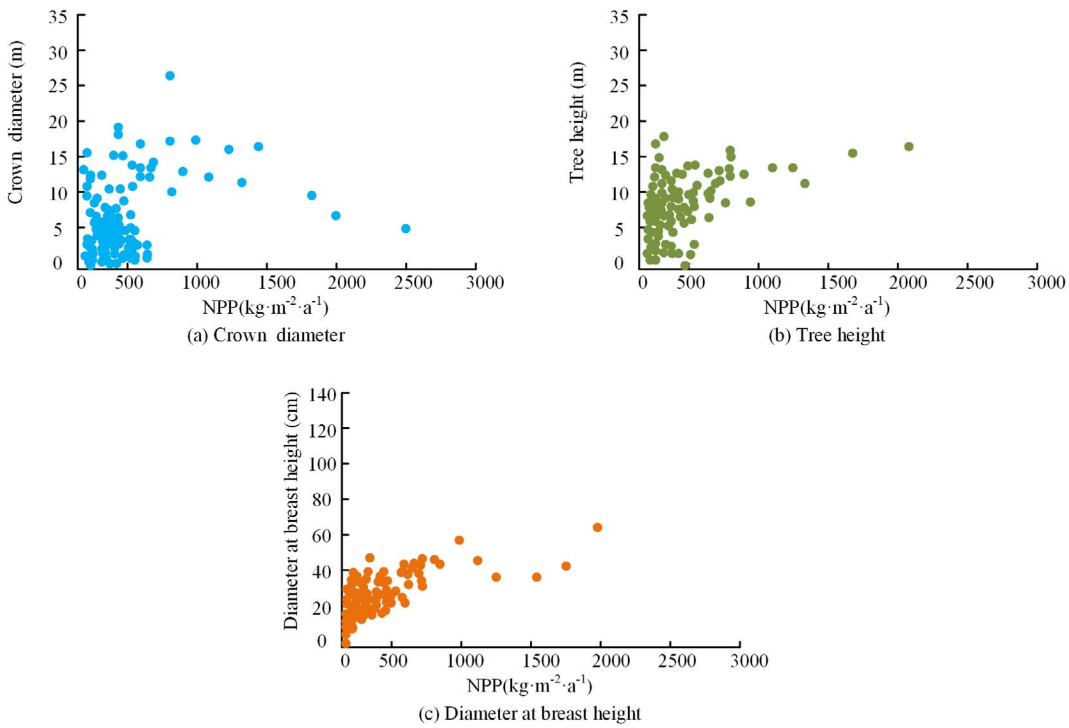

Figure 7. Analysis of the impact of various plant characteristics on NPP of vegetation.

Table 3. Quantitative results of carbon sources and sequestrations for two types of parks

Project		Nonsponge park	Sponge park	Improvement effect
Plant carbon sequestration		90 465.94	81 316.36	-10.11%
Soil carbon sequestration		2689.16	3243.59	20.62%
Terrain	Runoff reduction	241.65	493.61	104.27%
	Pollutant reduction	91.69	486.16	430.22%
	Rainwater purification	1664.06	6394.16	284.25%
Maintenance	Irrigate	23 923.95	14 681.16	-38.63%

were roughly divided into four CO_2Seq units. Based on the CO_2Seq characteristics, the optimization design of park green spaces was further achieved.

5 Discussion

In the construction of sponge-type parks, in order to meet the demand for runoff reduction and purification, the plant configuration of green space is restricted by LID facilities, resulting in a plant configuration that directly affects the play of the carbon sink function. Moreover, the operation and maintenance of LID facilities may partially offset their contribution to carbon sinks, and they cause certain interference and damage to the surrounding environment, affecting the play of carbon sink functions. Carbon sink analysis plays a key role in different fields. Valentine *et al.* [6] analyzed carbon sinks

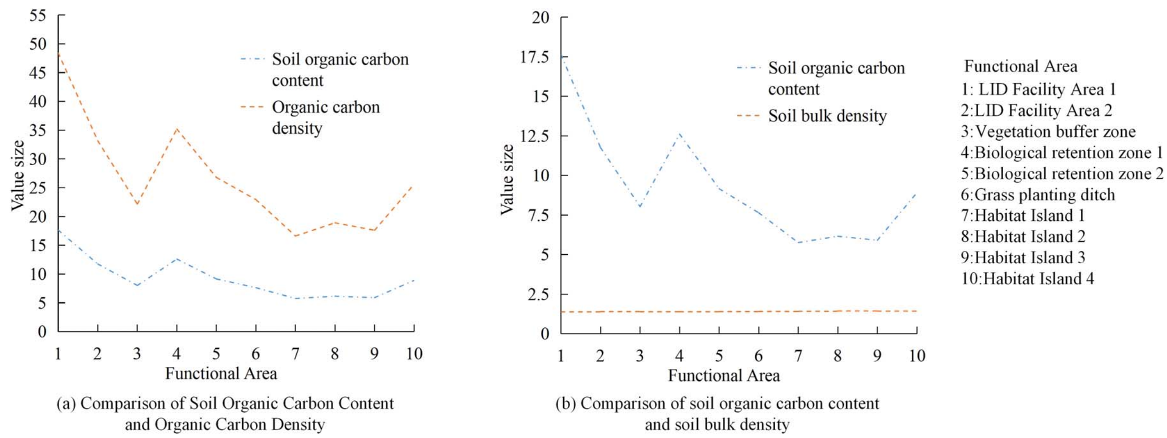

Figure 8. Impact mechanism of soil carbon sequestration in the LID facility area.

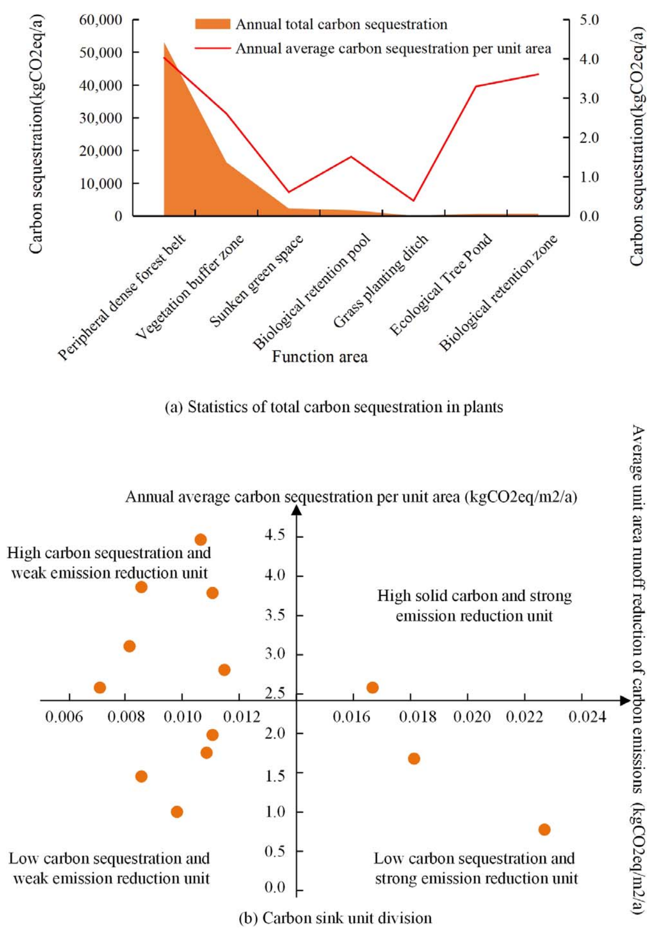

Figure 9. Analysis of carbon sequestration conflicts caused by LID facility areas.

in coastal ecosystems, Li *et al.* [7] developed the estimation of agricultural carbon emissions and carbon sinks, and Singkran [8] analyzed the carbon sink capacity of public parks, but the applicability of carbon sink analysis methods in different fields to sponge cities under LID facilities is low. In this regard, some researchers and scholars have also carried out carbon sink measurements for sponge cities. Ma *et al.* [21] evaluated the carbon emission reduction effect of sponge districts by taking the new residential district in Tianshui City, Gansu Province, as an example, and evaluated the carbon emission reduction effect of sponge districts based on the carbon emission factor method of the LCA carbon emission accounting model. The results found that the 30-year full life cycle carbon emissions of new residential areas in sponge cities were higher than those of traditional buildings, but the carbon reduction effect was significant, with a reduction of 47.31% in carbon emissions, and carbon neutrality was achieved in 22–30 years [21]. Jiang *et al.* [22] took the landscape nodes along urban rivers in Nanjing as an example to assess the sustainability of the landscape system by using the full life cycle energy-value method and the carbon emission method, and to predict its long-term sustainability by using an artificial neural network. The results showed that maintenance investment increased over time, leading to a decrease in system efficiency, and carbon emissions were mainly from diesel, cement, and steel [22]. However, the existing carbon sink measurement still lacks a systematic assessment of the carbon sink efficacy of sponge city parks and is unable to provide a comprehensive understanding of the changes in carbon sinks under different stages, facilities, and plant configurations.

Based on the above background, the study further focuses on sponge-type urban parks, and innovatively combines the existing carbon sink theory knowledge to design a set of methods that can quickly quantify the carbon sinks of sponge-type urban parks. By quantifying the total amount of carbon sinks in sponge-type urban parks and conducting sensitivity analyses of carbon sink elements, the study identifies the impacts of different factors on the park's carbon sink capacity, thereby guiding future design and management strategies to maximize the benefits of carbon sinks. In addition, the study explored the impact of LID on carbon sinks in sponge-type urban parks, revealing the potential of LID in enhancing the ecological functions of urban parks, especially the carbon sequestration capacity. In summary, the study provides new perspectives and practical guidance for urban green space planning, management, and climate change mitigation by designing a rapid quantification method for carbon sinks in sponge-type urban parks and conducting sensitivity analysis of carbon sink elements and impact analysis of LID.

6 Conclusion

To further improve the CO_2Seq quantification of urban parks and achieve low-carbon and sustainable development of cities, a CO_2Seq quantification method for sponge city parks was designed based on CO_2Seq theory analysis. The experimental results indicated that direct CO_2Seq contributed the most to the CO_2Seq of the park, followed by rainwater purification by LID facilities. The sensitivity of plant CO_2Seq function and diameter at breast height to CO_2Seq benefits was 89.67% and 78.94%, respectively. The sensitivity of pruning method was the lowest, at 4.91%. The sensitivity of irrigation methods to CO_2Seq efficiency was 21.05%, and crown width, tree height, and diameter at breast height had a significant effect on NPP. Compared with nonsponge parks, the plant CO_2Seq and irrigation carbon emissions of sponge parks were 90 465.94 and 23 923.95 kgCO_2eq/a, respectively, with a decrease of 10.11% and 38.63%. The planning and design of urban parks should consider the bidirectional effect of LID facilities on CO_2Seq efficiency. Based on the carbon sink theory, the study designed an innovative carbon sink quantification method for the characteristics of sponge-type urban parks. The method not only considers the direct carbon sequestration of the park, but also incorporates the indirect carbon sink contribution of LID facilities to rainwater purification, which enriches the theoretical system of carbon sink quantification in urban parks. The study deeply analyzes the bidirectional role of LID facilities on the carbon sink benefits of sponge-type urban parks, which fills the gaps in the research in this field and helps to comprehensively understand the mechanism of the role of LID facilities in the carbon sink of urban parks. The results of the study can provide guidance for the planning and design of urban parks, especially in the selection of plant species and the configuration of LID facilities in order to maximize the carbon sink benefits of the parks. However, the study does not analyze the CO_2Seq benefits, and future research work can further explore them.

In the process of future urban development, it is recommended that the government strengthen the assessment of the carbon sink capacity of urban parks during the planning, construction, and operation of the parks, and make the carbon sink benefit one of the important indicators for park planning. At the same time, it is encouraged to widely apply LID facilities in urban parks, especially those that have a significant positive impact on carbon sink benefits, such as green roofs and bioretention ponds.

Author contributions

Peng Liu (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Writing—original draft [equal]), Feng Quan (Data curation [equal], Investigation [equal], Validation [equal], Visualization [equal]), Yuxuan Gao (Data curation [equal], Investigation [equal], Methodology [equal]).

Conflict of interest

The authors declare that they have no competing interests.

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Data availability

All data generated or analyzed during this study are included in this article.

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