Research on Carbon Sequestration of Building

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Abstract. This paper briefly introduces the background, theory and recent achievements of building carbon sequestration, and introduces in details of the calculation method and the research characteristics, operability and shortcomings of this method. It points out that the model has conceptual visualization, rich connotation and its role in the design of low-carbon urban space, and its influence factors on the layout of low-carbon space are obtained from the determination of coupling building carbon sequestration according to the area of building units and patches. Finally, the current research trends and methods are reviewed and prospected, and it points out that its the whole life cycle and multi-scale and multi-objective influence mechanism can play a guiding role in the spatial layout of low-carbon cities.

Keyword: Carbon sequestration; Urban design; Spatial distribution

1. Introduction
With the increasingly serious deterioration of the earth's environment, the study of global carbon emissions and carbon absorption has become one of the core environmental issues. Reducing carbon emissions and increasing carbon absorption are the main ways to effectively reduce urban greenhouse gases. The traditional research theory holds that the main body of carbon sequestration is mainly green space, water, soil and so on. However, foreign research results reveal that concrete in buildings continue to absorb CO₂ in the environment when exposed to the air [1]. According to the research of American Portland Cement Association, the total carbon sequestration of existing buildings in the United States is about 200000 tons in one year after construction. China is a big cement producer, accounting for about 60% of the world's cement output and consumption. Between 2011 and 2013, China consumed 6.6 billion tons of cement, surpassing the 4.5 billion tons consumed by the United States throughout the 20th century.

At present, the research on urban carbon sequestration mainly focuses on water, soil vegetation and other natural carbon sequestration, but there is little research on artificial carbon sequestration. In terms of the total amount of urban carbon sequestration, building carbon sequestration is an important part of artificial carbon sequestration, contributing a lot to the overall carbon absorption of the city. Research shows that carbon dioxide emissions from cement production account for 5% of global carbon dioxide emissions, while China's cement production and consumption account for more than half of the world's production and consumption. China's cement production process accounts for 9% of China's total carbon dioxide emissions. The latest research results collected from NATURE in the
United States show that during the carbonation of cement concrete and mortar, carbon dioxide in the air is absorbed and sealed in cement concrete and mortar materials [2]. Thus it can be seen that building carbon sequestration will have a great impact on the global carbon cycle in urban construction and other human activities.

2. Theoretical Background of Building Carbon Sequestration

The research on carbon sequestration at home and abroad mainly focuses on three aspects: ocean (water), soil and vegetation. Among them, the ocean is the most important part of the earth's carbon sequestration, and the amount of biological carbon sequestration per unit sea area is 10 times that of the forest and 290 times that of the grassland. For cities, the common carrier of carbon sequestration is mainly green space. Ye Zuda established a carbon sequestration function evaluation model based on urban and rural ecological green space, to establish a scientific, operational carbon sequestration function evaluation method with the new planning concepts and methods [3]. Ye Youhua, Zou Jianfeng, Wu Feng et al. analyzed the basic characteristics and improvement strategies of carbon sequestration resources in highly urbanized areas, and calculated the carbon sequestration of different types of land from the point of view of urban complex ecosystem [4]. Zhou Jian, Xiao Rongbo et al. explored the characteristics of urban forest carbon sequestration in two aspects: the temporal and spatial distribution of carbon sequestration and the relationship between urban forest and low-carbon development. The research on urban carbon sequestration abroad regards the city as an ecosystem and makes a comprehensive research and discussion on urban carbon sequestration in the aspects of urban ecosystem and climate change, urban forest carbon sequestration, lawn and residential landscape carbon sequestration, urban ecosystem development situation and management (Rattan Lal-Bruce..). The annual total carbon sequestration capacity of each tree was estimated to be 1.4kg - 54.5kg. Follet et al. studied different kinds of lawns and found that the annual net carbon sequestration of artificial lawns was 254kg - 2043kg per hectare.

Through the above research, it can be found that there are some in-depth studies on carbon sequestration of grassland, trees, soil and other natural resources at home and abroad. International and domestic scholars have researched a lot in carbon sequestration, and achieved certain results. Based on the relevant literature, the current research mainly focuses on the single ecosystem carbon sequestration theory, mechanism and carbon sequestration accounting, while the research on urban carbon sequestration resources is relatively fewer. Although some research has been done on urban carbon sequestration resources, mainly focused on forestry carbon sequestration research, there are few studies on urban carbon sequestration resources in terms of urban complex carbon sequestration system.

As a part of urban ecosystem, carbon cycle has its own system along with the flow of matter and energy [5]. Theoretically, the amount of CO₂ absorbed by hardened concrete, cement and lime during carbonation is the same as the CO₂ emission during the decomposition of calcium carbonate. If the time is long enough, carbonation can dissolve the cement of concrete and mortar and make it into calcium carbonate, silicon hydrate, alumina and iron oxide. If buildings exist, this process may take centuries to complete. However, only a very small proportion of buildings can exist for hundreds of years. Most buildings live for less than 100 years. Most studies do not take into account the effects of CO₂ on the demolition of buildings and the subsequent crushing and recycling of concrete. There are few studies on carbon absorption of cement mortar. Therefore, the carbon sequestration evaluation of cement should involve not only the use, removal, crushing and recycling of cement concrete, but also the absorption of CO₂ in carbon sequestration of cement mortar and cement kiln dust (CKD) [6]. The main types of cement used in construction are concrete and mortar. The carbonation of concrete is widely studied in civil engineering, while the carbonation of mortar is seldom studied. However, for reinforced or pre-stressed reinforced concrete, carbonation caused by alkalinity reduction can accelerate the corrosion of embedded steel bars. Mortar is a kind of fine aggregate concrete, with a high carbonization rate in pasting, smearing, decoration and maintenance in large open-shelf areas [7].

The earliest research on concrete carbon sequestration function is known in two research reports of
American Portland cement Association (PCA), which comprehensively discussed the influence of environment on concrete carbonation, the influence of cement composition on carbon absorption and the methods of carbon sequestration test and accounting, and estimated the in-use building carbon sequestration in the United States. It was found that in the first year after construction, the total carbon sequestration of a building could reach 200,000 tons. The building carbon sequestration rate is researched in civil engineering, mainly from the point of view of carbonation resistance of concrete [8]. The carbon sequestration depth of concrete of the in-use building is estimated, and the factors of carbonation rate such as temperature, humidity, exposure condition, porosity, water-cement ratio, strength grade, environmental CO$_2$ concentration, surface coating are experimentally analyzed. Scholars in this field have quantified the carbonation rate of concrete under different conditions through testing and statistical analysis. Only a small number of scientists have focused on the carbon sequestration function of concrete [9]. Nowak and Bureau et al. studied the carbon retention time, carbon absorption and carbon emissions in urban areas of the United States. In addition, from the perspective of building life cycle, the Nordic scientists Pade and Andersson adopted the life cycle assessment method to divide the accounting of concrete carbon sequestration function into carbonization in building use stage, building demolition stage, waste treatment and recycling stage, calculate carbon sequestration, test concrete carbonization parameters under different conditions, and analyze concrete carbon sequestration in Nordic countries. The accounting method of concrete carbon sequestration is established. The research makes a great contribution to quantifying the carbonation function of concrete, and the accounting method of concrete carbon sequestration is basically established [10].

Against the background of climate change and global emission reduction, ecological city and low-carbon planning and construction have become the mainstream of urban development in the world [11]. Urban spatial form has a certain locking effect on urban operation and city elements, and urban carbon sequestration is the core means of low-carbon urban planning, so the research on the relationship between urban spatial form and carbon sequestration space has gradually become a central issue [12]. Foreign research on low-carbon ecological city mainly includes the relationship between land use and carbon sequestration land, low-carbon city management, low-carbon community, ecological city, ecological community and so on. For example, the British city of Milton Keynes increase green elements and green space to build a “green city”. Some countries formulate ecological city standards and build a new type of ecological city: the United States, Australia, India, Brazil, Denmark, Sweden, Japan and other countries have put forward basic requirements and specific standards for ecological city construction [13].

At present, research on the relationship between urban spatial form and carbon sequestration in China is still in its infancy, and various methods are still being gradually improved. However, in terms of research methods, the corresponding research has changed from qualitative research to quantitative research, from single urban factor research to multi-factor comprehensive research. Ye Youhua et al. believe that in order to promote the construction of low-carbon ecological cities in highly urbanized areas, we must pay attention to the development of urban carbon sequestration resources and promote the continuous increase in carbon sequestration resources and the continuous improvement of carbon sequestration quality. Zhao Liang studied the temporal and spatial characteristics of carbon sources and sequestration in urban areas of Yinchuan Plain, and identified the main factors affecting the increase and decrease of carbon emissions and carbon sequestration. The balance and development trend of carbon sources and total carbon sequestration in Yinchuan Plain were discussed from the point of view of carbon cycle. Taking Nanning, Guangxi as an example, Qin Menglin put forward the concept of carbon source and carbon sequestration land, and considered that the carbon sequestration land in urban margin is mainly composed of cultivated land and garden land, and the protection of cultivated land and garden land has become the core task of increasing carbon sequestration land [14].

At present, although the existing studies have quantitatively analyzed the relationship between urban spatial form and carbon sequestration [15], urban carbon sequestration is often limited to natural carbon sequestration dominated by vegetation. However, the impact of artificial carbon sequestration...
dominated by urban building carbon sequestration on urban space has not been studied. In order to develop low-carbon ecological city, it is necessary to study the basic characteristics of urban building carbon sequestration resources, and add artificial carbon sequestration studies to the traditional natural carbon sequestration research to build a complete urban complex carbon sequestration resource system, so as to provide reference for the management of urban carbon sequestration resources.

To sum up, domestic and foreign scholars have made in-depth research on low-carbon urban planning methods and technologies, but the existing research on carbon sequestration mostly focuses on vegetation, soil, water and other natural carbon sequestration. Research on building carbon sequestration has not been carried out. In cities, the absorption of carbon dioxide by building carbon sequestration can not be ignored. Therefore, from the point of view of artificial carbon sequestration, this study will quantify the carbon sequestration coefficient of building carbon sequestration, extract the building capacity, and construct the spatial database of urban building carbon sequestration capacity. By analyzing the influence of urban planning on building carbon sequestration, this paper studies the urban low-carbon spatial layout optimization model based on building carbon sequestration capacity, puts forward a systematic urban low-carbon spatial layout optimization method, and improves the urban complex carbon sequestration system, so as to provide reference for low-carbon city planning.

3. Research Methods of Building Carbon Sequestration

In the study of urban complex ecosystem, we should not ignore the ecological process of air being absorbed by building carbon sequestration into the material cycle. Only by deeply revealing the impact of building carbon sequestration capacity and its spatial layout on the overall urban carbon absorption can we fully grasp the internal mechanism of urban carbon cycle and provide sufficient scientific basis for solving the problem of global climate change and forming low-carbon urban space.

3.1. Calculation Method of Urban Building Area

The primary premise of carbon sequestration calculation is to calculate the building area. In China, the main building volume survey methods with remote sensing include direct method, projection method, shadow method and height difference method. The direct method has the advantages of simplicity and high accuracy. However, it is only suitable for the calculation of volume ratio in small areas. In larger areas, the workload of data processing is so huge that it is difficult to use the direct method; the height difference method and projection method involve not only aerial imaging parameters, but also tedious photo measurement; the shadow length method is that inversion is done with the length of the shadow perpendicular to the building in the high-resolution remote sensing image. Firstly, the computer method of human interference is used to extract the length of shadow perpendicular to the building. This semi-automatic extraction method is that the operator should calculate the nearest distance of the corner first, then screen the length and angle, and finally carry on the statistical average, and the extracted shadow length is vectorized into the database. Then, with the measured building height, the relation coefficient between the shadow length and the actual building height is inverted. Finally, the shadow inversion height of the building is obtained by multiplying the vectorized shadow length by the inversion coefficient, and the number of floors of the building is decided according to the height range. The calculation method is as follows:
Suppose the height of the building is H, the actual length of the building shadow is S, the visible length of the building shadow is L2, satellite elevation angle is α, and solar elevation angle is β.

In the picture a, when the sun and the satellite are in the same azimuth, that is, when the sun and the satellite are on the same side of the building, the actual length of the building shadow is S=H/β, and the shadow length visible on the remote sensing image is:

\[ L_2 = S - L_1 = H/\tan\beta - H/\tan\alpha \]

In this case, the formula between the building height H and the visible shadow length can be obtained as follows:

\[ H = L_2 \times \tan\alpha \times \tan\beta / (\tan\alpha - \tan\beta) \]  

(1)

When the sun and the satellite are in the opposite direction, that is, when the sun and the satellite are located on both sides of the building, the actual length S of the building shadow is equal to the shadow length L2 visible on the remote sensing map. L1=0. So in this case, the formula between the building height H and the visible shadow length is:

\[ H = L_2 \times \tan\beta \]  

(2)

Therefore, we can know that there are two methods to calculate the building height through shadow.

1) If we know the relevant parameters of the satellite in the remote sensing satellite image, such as solar elevation angle, solar azimuth angle and satellite elevation angle, the height of the actual building can be obtained with formula (1) and formula (2) combined with the visible length of building shadow in the remote sensing image.

2) If the satellite parameters of the remote sensing satellite image are unknown and the satellite parameters in a remote sensing image are the same.

\[ K_1 = \tan\alpha \times \tan\beta / (\tan\alpha - \tan\beta) \]

\[ K_2 = \tan\beta \]

In any case, K1 and K2 are constant.

\[ H = L_2 \times K_i \ (i = 1, 2) \]

That is, the actual height of the building is proportional to the length of its shadow in the direction of sunlight projection in the remote sensing image. In this case, the Ki can be inversely calculated with
the actual height of a local building so as to calculate the height information of other buildings. A large number of building height information collected in the field in the early stage can be used not only to invert the parameter Ki, but also to monitor the inversion results.

### 3.2. Calculation Method of Urban Construction Capacity

The extraction of urban three-dimensional building capacity is based on high-resolution remote sensing images. Operators should divide the patches of homogeneous height, extract building contour information and building projection length information to obtain the index parameters such as the number of buildings in the patch, the building base area, and the building height through inversion. Finally, the building capacity of the homogeneous patch is obtained, thus having building area of each city.

In GIS, spatial data is of attribute, spatial and temporal characteristics, and the basic data types include attribute data, geometric data and spatial relation data. As the basic data type, spatial relation data mainly refers to the relationship of point to point, point to line, point to surface, line to line, line to surface, and surface to surface. According to the principle of the algorithm, it is much easier to judge whether a point in a polygon than to judge whether a polygon is in another polygon, so when counting the number of buildings with homogeneous height in the patch, we only discuss whether the geometric center is in the patch. Firstly, the vector plane data of building contour is transformed into vector point data (the point data represented by its geometric center), and then the algorithm of judging whether a point is in a polygon can be used to count the number of points in the patch, that is, the number of building contours with homogeneous height. The calculation method of patch construction capacity is as follows:

$$\text{Patch construction capacity} = \frac{\text{(single building projection area \times building height \times number of buildings in the patch)}}{\text{patch area}}$$

Firstly, the vector plane data of building contour is transformed into vector point data (the point data represented by its geometric center), and then the algorithm of judging whether a point is in a polygon can be used to count the number of points in the patch, that is, the number of building contours with homogeneous height.

After counting the number of buildings, the buildings in the patch can be randomly selected, and the average height and the average base area of the patch is taken as the height and bottom area of the randomly selected building with the homogeneous height.

### 3.3. Calculation Method of Carbon Sequestration in Urban Buildings

The calculation of building carbon sequestration is mainly for cement materials in urban buildings. Concrete carbonation is widely studied in civil engineering, while the carbonation of mortar is rarely studied. The durability of plain concrete does not affect carbonation and may even be improved. However, for reinforced or prestressed reinforced concrete, carbonation caused by reducing alkalinity can accelerate the corrosion of embedded steel bars [16]. Mortar is a kind of fine aggregate concrete, which shows a huge carbonization rate in laminating, smearing, decoration and maintenance in large open-shelf areas [17]. Fick's second law is used to calculate the carbonation depth of concrete, whose coefficient can be simplified considering different environmental factors. The amount of carbonated cement concrete and mortar is related to exposure time and surface area. For each type of concrete with a given environment, the carbonation depth is calculated as follows:

$$d = K t^{1/2}$$

In this formula, d is the carbonation depth in millimeter; k is the carbonization rate coefficient; t is the term.

T is the term of the building structure. In an ideal environment and operation conditions, t must be designed and built to maintain the safety and stability of the structure during its service. The k is used to correct a constant for the most important concrete and environmental type, given the increment of compressive strength, contact conditions, temperature, relative humidity, surface crack and type, as
well as CO\textsuperscript{2} concentration and outer surface cover, etc. The actual term of most buildings is less than their designed one, especially in many developing countries, such as China. According to the literature, the typical carbonation rate of concrete ranges from 0.15 to more than 20 mm / half a year. Neville found that the typical carbonation rates of 20MPa and 40Mpa concrete are respectively 7.1mm and 2.5mm per half a year.

4. Model Evaluation of Building Carbon Sequestration

4.1. Characteristics and Innovation

4.1.1. Vivid Concept and Rich Connotation. The concept of building carbon sequestration is based on the grid division of urban plane, and the spatial database of urban building carbon sequestration capacity is established by using the method of projection area and height inversion. The concept reflects the relationship between building carbon sequestration and spatial distribution from a three-dimensional scale, providing a basis for studying the urban artificial carbon sequestration system with architecture as the main body and perfecting the urban complex carbon sequestration system.

4.1.2. Comprehensive and Novel Theoretical Angles. This research is different from the previous studies on carbon sequestration, which is mostly limited to the study of natural entities such as forest, farmland and other vegetation in their carbon storage, carbon sequestration rate, carbon sequestration potential and other carbon sequestration factors. This paper discusses the combination of urban planning and landscape ecology, studies the influence of urban planning and layout on the carbon sequestration capacity of buildings from the point of view of urban complex carbon sequestration system, and constructs the distribution model of urban building carbon sequestration capacity. The paper puts forward an optimization method of urban low-carbon spatial layout, providing reference for the ecological planning and construction of urban complex carbon sequestration space.

4.1.3. Design Method of Urban Space Based on Carbon Sequestration. Taking the urban building carbon sequestration as the main research object, this paper makes up for the carbon deficiency in the urban carbon cycle from the point of view of urban ecological function, and puts forward the urban low-carbon spatial layout pattern and spatial optimization method from the point of view of urban carbon sequestration spatial allocation, providing a basis for low-carbon city planning.

4.2. Operability

Through the establishment of a coupling model between building carbon sequestration capacity and urban spatial layout, this paper studies the nonlinear relationship among various factors (building shape coefficient, surface area parameters, time variables, etc. quantifies the building carbon sequestration coefficient to analyze the influence mechanism of various factors of urban space land type, functional zoning, development intensity, volume ratio and building height, layout form, etc. on building carbon sequestration capacity, revealing the spatial distribution law of urban carbon sequestration building capacity.

5. Research Review and Prospect

Recent researches have gradually introduced the concept of whole life cycle, and it can be known that temperature, humidity, exposure conditions, porosity, water-cement ratio, strength grade, environmental CO\textsuperscript{2} concentration, surface coating and other factors have a comprehensive impact on concrete carbonation. In the use stage of the building, the concrete carbonization rate parameters are different under different conditions; in the building demolition stage, the demolition mode, exposure time, particle size distribution of waste concrete and other factors affect the carbon sequestration of concrete, so it is necessary to carry out experiments and demolition sample testing to determine the carbonization parameters in the stage under different conditions. The carbonation ratio parameters of
waste concrete will be affected under the influence of different treatment and recycling methods, which will make the calculation of building carbon sequestration more accurate.

Most of the existing research results on carbon sequestration are based on the measurement of urban or regional biomass indicators, but there is little research on the carbon sequestration of cities or blocks. The low-carbon planning method, based on the relationship between urban spatial form and carbon sequestration pattern, includes four key steps: development mode selection, urban structure division, plot capacity limitation and planning layout formation. On the urban scale, according to the spatial relationship between the distribution law of urban building carbon sequestration capacity and urban natural carbon sequestration, the spatial regulation and control scheme of urban complete carbon sequestration is put forward to construct an urban complex carbon sequestration system based on ecological function. On the block scale, operators can select a typical (in a residential district / an urban high-density area) block as the research object, analyze the quantitative relationship between building carbon sequestration capacity and natural carbon sequestration layout, and form a low-carbon layout optimization model. Research can be done in analyzing the relationship between building carbon sequestration capacity, development intensity, functional zoning, layout and spatial combination to reveal the differentiation law of urban carbon sequestration building space and expound the influence mechanism of urban spatial characteristics on building carbon sequestration capacity, providing theoretical support for the establishment of urban low-carbon space layout optimization method.

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