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A review of research methods for accounting urban green space carbon sinks and exploration of new approaches

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Along with urbanization and industrialization, carbon emissions have been increasing significantly, resulting in global warming. Green space has been widely accepted as a natural element in cities to directly increase carbon sinks and indirectly reduce carbon emissions. The quantification of carbon benefits generated by green space is an important topic. This paper aims to provide a comprehensive review of the methods for measuring carbon sinks of green spaces. The results indicate that existing assessment methods can accurately estimate the carbon sinks in green spaces at large scales. However, existing methods are not fully applicable to studies of urban green spaces, due to the low precision of research results. The assimilation method is the most suitable method to study the carbon sequestration efficiency of plants and can project the carbon sinks of urban green spaces at large scales through macroscopic means. Even though, the results of assimilation experiments are unstable under different weather conditions. To address existing research challenges, this paper proposes a photosynthetic rate estimation method based on the light-response curve which is an efficient method to describe the relationship between light intensity and net photosynthetic rate in studying plant physiological characteristics. The newly proposed method, through integrating net photosynthesis-light response curves and urban light intensity associated with meteorological data, has advantages of short measurement time and ensuring standardized experimental environment for result comparability. Overall, this study is important to combine meteorology and plant physiology to propose a photosynthetic rate estimation method for optimizing carbon sink measurement in urban green spaces. The method is more convenient for application for its simple experimental process and result comparability. In practice, this study provides guidance for low-carbon urban green space planning and design, and helps to promote energy conservation and emission reduction through nature-based solutions.

KEYWORDS

urban green space, carbon sinks accounting, photosynthetic rate estimation, net photosynthetic light-response curve, photosynthetically active radiation

1 Introduction

1.1 Urbanization, greenhouse gas emission, and global warming

With the predominant industrialization and urbanization, the construction of urban infrastructure and land use changes have dramatically replaced natural ecosystem areas (He et al., 2021), resulting in significant environmental deterioration, economic losses, social challenges, and public health issues (Li K. et al., 2023; He, 2023; Wei et al., 2023). Addressing such challenges have been a consensus of the public, governments and organizations (Liu X. et al., 2023). Even though, cities are highly dependent on heavy fossil-fuel use. Authorities estimate that fossil fuel combustion accounts for 90% of total CO_2 emissions in 2023 (Friedlingstein et al., 2023), resulting in a rapid rise in atmospheric concentrations of greenhouse gases on Earth, ultimately causing global warming (Gao et al., 2021; Shen and Zhao, 2024). For example, a 1.1°C increase in global average temperature worldwide presents the largest increase in the last 1,000 years (Intergovernmental Panel On Climate Change, 2023). Furthermore, it is reported that the urbanization has contributed to one-quarter of the average annual temperature increase of Guangdong Province in the last 70 years (Zhong et al., 2023). The atmospheric studies in Guangdong, Hong Kong, and Macao in China have concluded that greenhouse gases are the most important determinants of future average and extreme temperatures (Zheng et al., 2022).

The global atmospheric CO_2 concentration in 2022 will be about 1.5 times that of the pre-industrial revolution, in addition to total global CO_2 emissions of about 40.9 billion tons in 2023, of which China will be the largest emitter, accounting for about 35% of the total emissions (Friedlingstein et al., 2023). Cities only cover 3% of the Earth's surface, but they are now representing more than 55% of the global population. Moreover, the spatial distribution of carbon emissions in cities are much higher than rural counterparts, indicating that cities and their adjacent regions are among the highest contributors to carbon emissions (Figure 1). In China, the situation is more alerting since urban areas contribute as much as 90% of national carbon emissions (Li, 2010). With this background, the United Nations Framework Convention on Climate Change was signed by more than 150 countries in 1992, in order to collectively maintain atmospheric greenhouse gas concentrations at a stable level. The 2015 Paris Agreement requires all signatory nations to reduce their greenhouse gas emissions. In September 2020, China explicitly set a double carbon target for 2030 in order to achieve carbon neutrality by 2060.

1.2 Significance of green spaces for climate change mitigation

Achieving carbon neutrality generally involves two primary approaches: carbon emission reduction and carbon sink augmentation. Carbon reduction is the ability of green spaces to reduce energy consumption in buildings, transportation, etc., by improving the microclimate of the space. The carbon sequestration is to increase the carbon sequestration capacity of greenfield plants, with a focus on strengthening the ecological construction and protection of urban green spaces. The terrestrial biosphere shows significant potential for carbon sequestration. The studies indicate that in China, the terrestrial biosphere annually sequestered an average of approximately 1.11 (±0.38) $\times 10^9$ tons of carbon dioxide between 2010 and 2016, roughly equivalent to 45% of the concurrent annual anthropogenic carbon dioxide emissions (Wang J. et al., 2020). Urban green spaces represent primary green ecological resources in densely populated and economically developed urbanized regions. These spaces also constitute the main natural carbon sinks within urban ecosystems and possess a unique ability for self-purification and self-regulation. It is demonstrated that urban green space contributes to improving urban environmental quality by sequestering carbon (Nowak et al., 2018). This is mainly manifested through vegetation employing photosynthesis to reduce

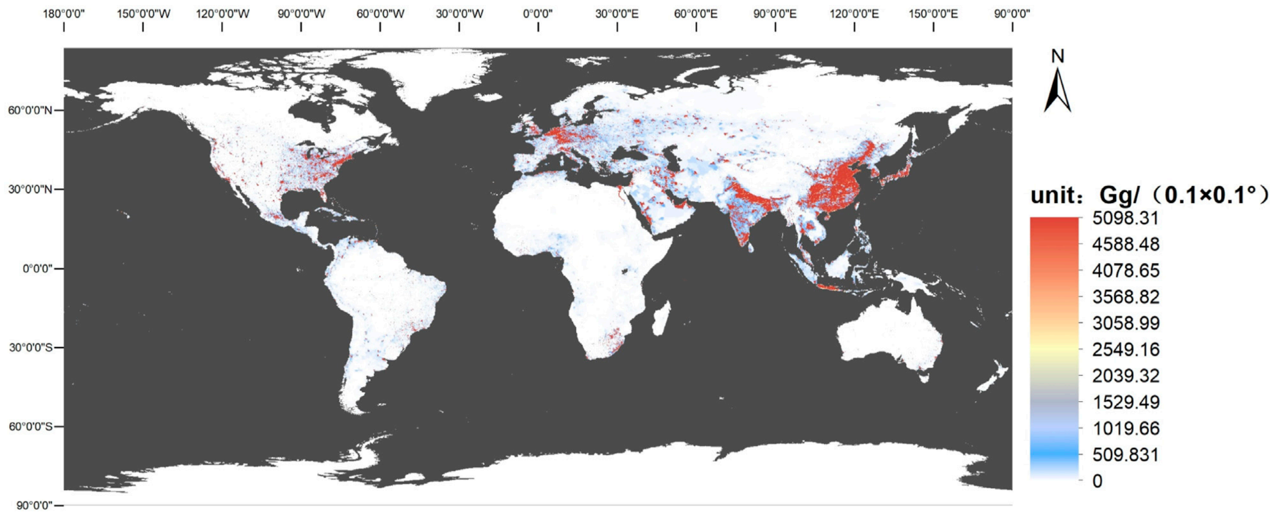

FIGURE 1
Global distribution of total carbon emissions in 2022 (source: Global carbon atlas).

atmospheric CO_2 while releasing O_2 (Russo et al., 2014), playing a crucial role in regulating the balance of atmospheric carbon and oxygen, and enhancing urban environmental quality.

Urban greenspace ecosystem comprises individual plant entities within the city, and its carbon sequestration capacity relies on the carbon sequestration abilities of vegetation. Urban green space vegetation serves as the main component of urban greenspace carbon sinks. Through photosynthesis and respiration within their leaves, plants accumulate a net carbon amount, sequestrating CO_2 within the vegetation, soil, and water bodies, thereby reducing atmospheric CO_2 concentrations (Dong and He, 2023). Moreover, urban green spaces effectively mitigate heat islands (Liu H. et al., 2023), decrease urban energy use, and thereby reduce urban carbon emission. Plants play a dual role of reducing CO_2 emissions and increasing CO_2 sequestration, making them the primary carbon sink in landscape architecture (Bao, 2011). Overall, ecosystem carbon sequestration, including urban greening carbon sinks, has become a focal task in the top-level design of China's efforts toward achieving carbon neutrality. To address warming challenges, it is essential to include more carbon sinks during urban planning and design to sequestrate greenhouse gases such as CO_2 and CH_4, as well as to alleviate environmental deterioration such as urban flooding and heat islands. Quantitative analysis of the carbon sequestration capacity of plants is an important research topic since it not only comprehensively demonstrates their carbon sequestration and oxygen release abilities and influencing factors but also provides the basis for creating, designing, managing, and improving urban natural carbon sinks. Furthermore, the quantitative analysis aids in scientifically selecting tree species for urban green spaces in a low-carbon era, offering theoretical references for strong carbon sink plant configurations, ecological landscape construction, and the development of eco-friendly urban landscapes. Overall, the quantification of green space carbon sink potential is a crucial means for alleviating global greenhouse and heat island effects, serving as a key player in supporting sustainable urban development and mitigating climate change.

2 Green space carbon sink: progress and status

In 1992, the United Nations General Assembly defined the process, activities, and mechanisms to remove CO_2 from the atmosphere as carbon sink. Green carbon sink, accordingly, involves the release of oxygen through plant photosynthesis, absorption of atmospheric CO_2, and its sequestration within vegetation and soil, thereby reducing CO_2 concentration in the atmosphere (Dong and He, 2023). Carbon sequestration is the process of capturing and securely storing carbon, as an alternative to directly emitting CO_2 into the atmosphere. A fundamental principle of plant carbon sequestration is that green plants utilize chlorophyll and other photosynthetic pigments under visible light for their growth requirements, converting CO_2 and H_2O into organic compounds, while releasing O_2 to maintain the balance of carbon and oxygen in the air. Note that plants can absorb only atmospheric CO_2 through photosynthesis (King et al., 2012) so that converting carbon sink quantity into CO_2 absorption is a more direct chemical quantification method. The capacity of plants to absorb atmospheric CO_2 depends primarily on the intensity of their photosynthetic activity which is often represented by the photosynthetic rate. The photosynthetic rate refers to the speed at which photosynthesis sequestrates CO_2 (or generates oxygen). The net photosynthetic rate signifies the organic matter accumulated through plant photosynthesis and is derived by subtracting the respiration rate from the total photosynthetic rate, serving as a determinant of a plant's carbon-fixing ability (Wang et al., 2014). It is commonly measured by a portable photosynthesis system (PPS).

Studies on plant carbon sequestration began in the 1960s and has gradually grown into an important research topic over the past decade, yielding significant accomplishments. For instance, in 1991, Rowntree and Nowak estimated the carbon stock of urban forests across the United States (Rowntree and Nowak, 1991) and concluded that green spaces could sequester CO_2 by regulating local urban conditions such as temperature and humidity. Subsequently, estimates of annual carbon sequestration in urban green spaces were conducted (Nowak et al., 2002; Pataki et al., 2006), enlightening many studies on urban ecosystem carbon storage. Presently, research on the carbon sink potential of garden plants primarily involves macro-scale estimations (i.e., the methods of sample plot measurement, model calculations, remote sensing (RS) estimation, and micrometeorological) and micro-scale measurements (e.g., assimilation) (Figure 2). However, these estimations are different in methods, accuracy levels, and requirements.

At macro scale, the research is primarily focused on carbon sequestration and storage quantification in extensive ecological systems (e.g., forests), from the perspective of plant carbon storage capacity in the agricultural and forestry-related domains (Houghton et al., 1985). Regarding the total carbon storage estimation of urban or natural green spaces, the macro-level approaches allow people to understand the carbon sink benefits of ecosystems, and thereby support and formulate urban forestry policies (Garcia-Gonzalo et al., 2007). Empirically, relevant studies were found before 2010, focusing on quantifying carbon sequestration in vegetation within green spaces (Paw U et al., 2004), yet macroscopic research methods were unable to estimate the net production within ecosystems or plants (López et al., 2010). Nevertheless, these methods are used as a basis for developing process-based simulations and models. Physiological measurements using infrared gas analyzers for CO_2 assimilation in plant leaves and branches, complemented by leveraging Earth observation technologies (e.g., satellite data), are used to extrapolate these measurements to larger scales (Holifield Collins et al., 2008).

At micro scale, primarily from the perspective of plant physiological characteristics, the quantification of carbon sequestration in plants during the process of photosynthesis is carried out by directly measuring flux difference using PPS to quantify their carbon sequestration. Since the 1950s, infrared CO_2 gas analyzers have been widely employed, with a fundamental principle of calculating net photosynthetic rate by measuring the difference in the CO_2 concentration entering the leaf stomata. These analyzers have shown innovation in measurement accuracy, efficiency, applicability, and data storage and are particularly suitable for outdoor measurements. Therefore, the assimilation method has been widely used for quantifying carbon sequestration of individual plants.

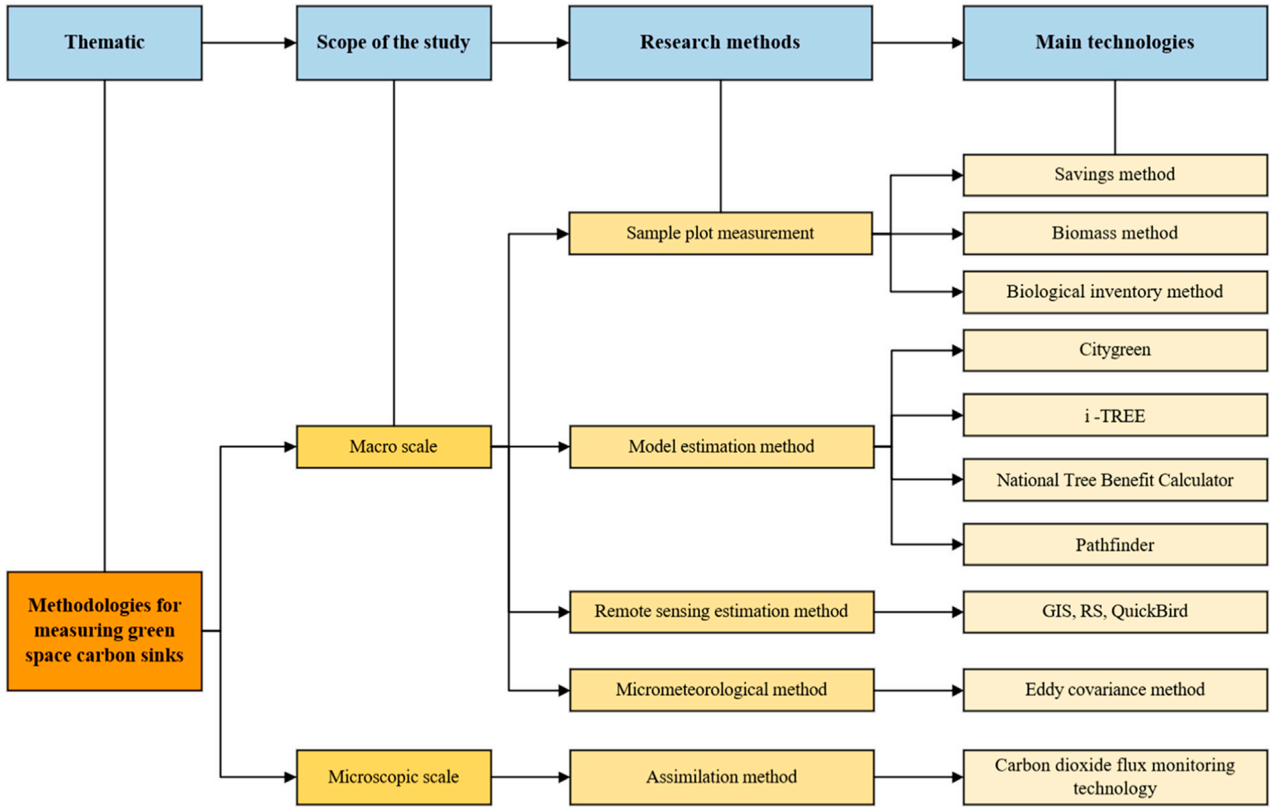

FIGURE 2
Summary of research methods and techniques.

2.1 Sample plot measurement

Sample plot measurement refers to an estimation method of setting up sample plots in typical areas with good forest growth and conducting continuous observation in the sample plots to obtain the changes in carbon stocks per unit time (Zhou et al., 2013). This method quantifies growth over time, considering the time when plants start growing until the time of their harvest. It is mainly applied to investigating the carbon sink potential of macro-scale green spaces. There has been a long history of sample plot measurement application, mainly in forestry and agricultural production, and it is a well suggested method by the IPCC for forest carbon sink assessment (Ouyang et al., 1999). This approach estimates the carbon sequestration of plants by harvesting and weighing all aboveground and belowground organic matter within sampling plots. The average values from these plots were used to estimate the biomass of the entire forest or individual plants, which were then converted into an average annual carbon sequestration rate for green vegetation.

In practical applications, it often involves the use of highly accurate measured data obtained from standard tree analysis to construct ecological indicators and biomass growth equations (Lee et al., 2014). For instance, the relationship between diameter at breast height (DBH), tree height and age indicators of trees was utilized to develop an allometric growth equation to estimate the carbon sequestration capacity of forests (Zhang et al., 2019). The biomass method acquires measured data through extensive field surveys to assess the biomass of plants at different time and measure their photosynthetic intensity. Overall, it is now the most commonly used method for calculating forest carbon storage because of its direct, explicit, and technically straightforward advantages. However, it has several limitations, such as destructive experimentation, inability for continuous observation, difficulty in accounting for root production and litterfall, and complex processing procedures.

2.2 Model estimation method

The model estimation method, based on a plot inventory, is a convenient and precise approach suitable for quantifying carbon sequestration of urban green spaces in large areas or urban regions. By the end of the 21st century, leveraging big data systems, the United States Forest Service, systematically analyzed and developed several convenient plant carbon sequestration calculation systems. At current, the widely utilized systems include Citygreen, the NTBC (National Tree Benefit Calculator), Pathfinder, and the I-Tree Eco. These models receive extensive application in assessing the ecological benefits of urban green spaces. For instance, the Citygreen calculation system, in conjunction with on-site surveys, has been employed to estimate the total carbon sequestration of green spaces in cities like Shenzhen (Chen et al., 2009), Shanghai (Xu, 2010), and Shenyang (Liu et al., 2008). And quantification of carbon sequestration benefits of green space plants in Nanjing residential area using NTBC (Li Q. et al., 2023). The I-Tree Eco module has been used in cities in the United Kingdom (Monteiro et al., 2019), the United States (Ning et al., 2016), Thailand (Intasen et al., 2017), and Hungary (Kiss et al., 2015) to assess the ecological value of urban green spaces. Moreover, the I-Tree Eco can estimate the carbon sequestration of individual plants based on specific characteristics. Overall, these estimation systems estimate carbon sequestration on a large regional scale by considering vegetation characteristics, meteorological data, site features, greenspace area, and surrounding environments so that the results are comprehensive. However, it is important to note that the physiological, ecological, and climatic parameters of the associated models were calibrated based on the U.S. conditions. Consequently, when such methods are applied to regions with different ecological systems and climatic conditions, substantial errors may occur. Therefore, these models are primarily suitable for use in areas with geographical and climatic conditions similar to those in the United States, upon some essential validation.

2.3 Remote sensing (RS) estimation method

The RS method, using satellite remote sensing to acquire various vegetation status parameters, offers the advantage of rapid, real-time, and large-scale data acquisition. It can well address the limitations of model-based estimations. The basic principle is to obtain various parameters of vegetation within the survey areas by sensing techniques on the basis of ground survey, and to estimate the impact of changes in land use and green space coverage on carbon stocks through spatial classification of vegetation and analysis of time series. Sensing-based assessments of net ecosystem productivity (NEP) are widely applied in carbon sink studies at regional and urban scales, such as some studies utilized QuickBird, RS and GIS to estimate the annual CO_2 uptake per tree in Los Angeles (Mcpherson et al., 2008), and combined LiDAR with QuickBird to estimate carbon stocks in urban trees (Schreyer et al., 2014). Meanwhile, there are studies on the use of remote sensing-based explicit forest carbon stock calculation models to realize high-resolution mapping of forest carbon stocks at large scales and dynamic monitoring of forest carbon sinks globally (Zhu et al., 2024), as well as the combination of ground-based measurements and LiDAR data to estimate the carbon stocks of urban trees (Gülin and Bosch, 2021). Research on the surface carbon storage of urban green spaces in Auckland also used LiDAR data combined with field surveys, suggesting that this approach not only provided more accurate data but also reduced the frequency and cost of actual measurements (Wang V. et al., 2020). This is because the method can offer detailed information on plant biomass in complex urban areas (Alonzo et al., 2014). However, due to the spatial heterogeneity and temporal dynamics of urban green spaces, the use of RS estimation methods for estimating carbon storage may encounter challenges like the inability to accurately determine plant quantity and difficulties in separating overlapping tree canopy boundaries (Richardson and Moskal, 2014). In addition, individual ecological differences among species can also lead to significant errors.

2.4 Micrometeorological method

The micrometeorological method is based on microclimate monitoring and involves continuous dynamic monitoring of near-surface atmospheric flow conditions and atmospheric CO_2 concentrations. This approach indirectly estimates the carbon flux of vegetation (Liu et al., 2018). It focuses on the quantitative study of carbon dioxide and water exchange between the atmosphere and terrestrial ecosystems (Grimmond et al., 2002). In Phoenix, the micrometeorological method was adopted, revealing that CO_2 concentrations at midday were lower than before sunrise mainly due to the strong sunlight at midday which promotes photosynthesis in vegetation (Idso et al., 1998), while in Essen using mobile measurement, it was shown that CO_2 concentrations in the city were lower in summer months given vegetation photosynthesis and other effects (Henninger and Kuttler, 2010). The micrometeorological method can accurately estimate regional-scale carbon fluxes, with eddy covariance being the most commonly used method. For instance, Velasco et al. used the eddy covariance method to show that urban CO_2 concentrations are lower during the daytime during the plant growing season, mainly due to the high photosynthetic capacity of plants at this time of year (Velasco and Roth, 2010), similar to the conclusion reached by Rana et al. (2021). Although the micrometeorological method allows for continuous *in-situ* observations, the unstable near-surface atmosphere and replicated topographic conditions can introduce significant errors into the results (Wilson et al., 2002). For example, atmospheric inversion and data from the Shangri-La observation point in the complex terrain of the Hengduan Mountains resulted in higher estimated data (Wang J. et al., 2020). The micrometeorological method also relies on site-specific observations and cannot represent carbon flux values for the entire region. At the regional scale, there are challenges related to low spatial resolution, making it difficult to differentiate the carbon sink amounts for different ecosystems (Piao et al., 2022).

2.5 Assimilation method

The assimilation method is a micro-scale research method. Since leaves are the most important organs for photosynthesis in trees, the assimilation method calculates plant carbon sequestration by determining the instantaneous net photosynthetic rate per unit of leaf area from the instantaneous CO_2 concentration of the leaves and the change in water content. Infrared Carbon Dioxide Gas Analyzers have been widely used from the 1950s to the present day, and the basic principle of their work is to calculate the net photosynthetic rate by determining the difference in CO_2 concentration entering leaf stomata. Measurements of photosynthesis rates of Wisconsin field species in the 1990s were an early application of the use of PPS to measure net photosynthetic rates of plants (Reich et al., 1995). By the end of 20th century, some studies reported the adoption of a photosynthesis meter to quantify plant photosynthetic intensity in a representative urban green space in Guangzhou and estimated the CO_2 uptake of the plants through the reaction equation of the photosynthesis process (Yang, 1996). Using infrared gas analyzers, measurement of the annual carbon dioxide uptake by urban plants in Korea was conducted, resulting in an empirical formula for future estimation. Furthermore, Han proposed a method for calculating plant carbon sequestration and oxygen release using the net assimilation rate formula (Han, 2005). The assimilation method experiment requires only a small amount of plant leaves, making it friendly to plants and widely applicable, and it has been employed in studies on common garden plants in locations such as West Bengal (Biswas et al., 2014), Rome (Gratani et al., 2016), and Fuzhou (Wang, 2010).

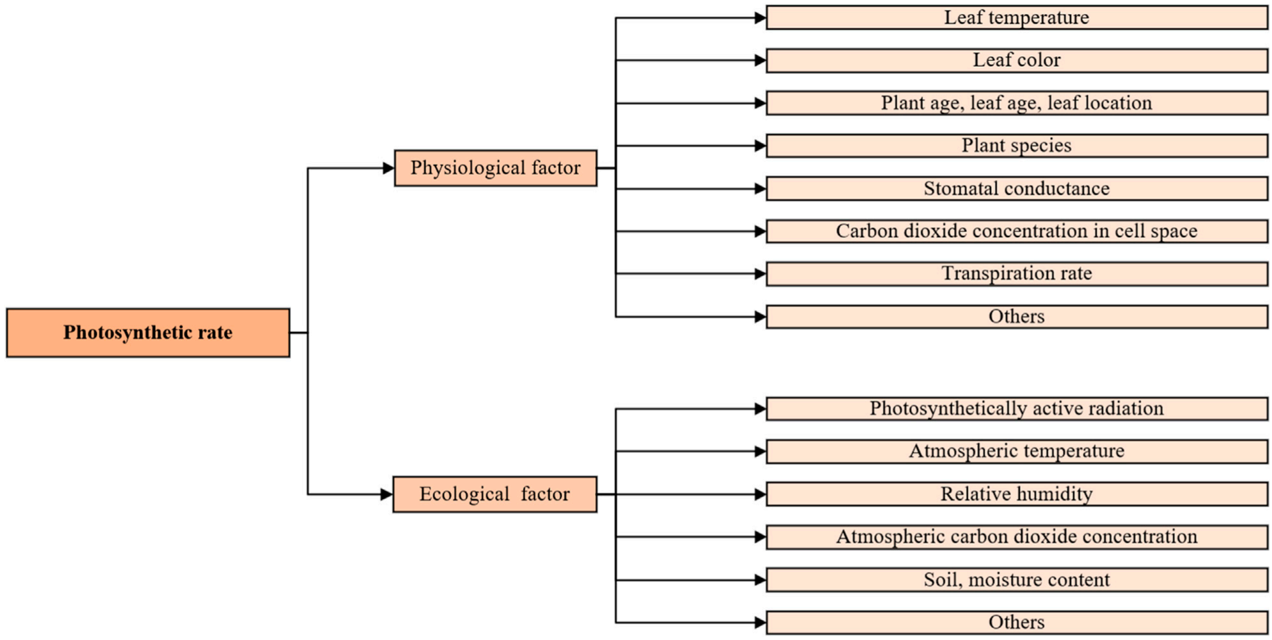

FIGURE 3
Photosynthesis-related influencing factors.

The assimilation method directly measures the carbon sequestration capacity of a single plant, and the results are accurate, allowing a direct comparison of carbon sequestration benefits among different plants. However, its outcomes are significantly influenced by temporal and spatial factors. This is attributed to the rhythmic cyclical variations in the photosynthetic rate of plant leaves, which systematically fluctuate with diurnal and seasonal changes. The primary rationale behind these fluctuations is the close relationship between photosynthetic rates and physiological and ecological environmental conditions such as atmospheric temperature, relative humidity, and solar radiation (Figure 3) (Evans and Santiago, 2011). For instance, the impact of vertical illumination results in peak solar radiation and daylight duration during the summer in the northern hemisphere, leading to a noticeable increase in carbon fixation by plants during this season compared to others. Although winter exhibits relatively weaker carbon fixation capacity throughout the year, the method still remains a high efficiency (Weissert et al., 2017). Moreover, air with higher relative humidity enhances stomatal conductivity in plant leaves, thereby elevating the rate of photosynthesis (Wang et al., 2019). These conditions necessitate labor-intensive hourly measurements of plant photosynthetic rates and impose significant requirements on weather conditions.

2.6 Summary

Whilst there have been many methods for urban green space carbon sink estimation, the advantages and disadvantages of each method are distinct (Table 1). Furthermore, there is no direct way to quantify carbon sinks in urban green spaces, and existing studies on urban green space carbon sink often employ methodologies developed for forest carbon sink (Gratani et al., 2016). Urban green spaces, primarily composed of artificial greenery, differ significantly from natural green spaces such as forests and grasslands. Urban green spaces also exhibit high heterogeneity, with plant species determined by early urban planning, incorporating both local and introduced species. This prominent contrast with naturally evolved green spaces implies that carbon sink in urban green spaces is more complex (Zhao et al., 2023). Therefore, existing methods for green space carbon sequestration may not be entirely applicable to urban settings. The sample plot measurement suitable for large-scale natural environments like forests, faces limitations in regions with diverse tree species distributions, rendering standard plots dissimilar to the entire region. Moreover, its destructive nature, involving irreversible vegetation removal, makes it unsuitable for urban green spaces designed and constructed through human planning. Explorations into non-destructive methods, such as the biomass method, for studying carbon sequestration in Bangkok park green spaces have been undertaken (Singkran, 2022), and the use of remote sensing to quantify and map forest structure to estimate forest above-ground biomass to quantify carbon stocks and fluxes in tropical forests (Mohd Zaki and Abd Latif, 2017), these studies explore additional possibilities for the sample plot inventory method.

Micrometeorological methods demonstrate high accuracy in regional-scale estimations but are sensitive to variations in urban spatial characteristics, leading to significant errors in different regions. Results from these methods reflect carbon sequestration at the regional scale and cannot discern individual plant carbon sequestration at a finer level. Model estimation incorporates green space information from similar regions into the model for estimation, potentially introducing errors due to ecological differences between regions. RS estimates carbon sequestration by calculating various green quantity indicators from satellite imagery, but the considerable variations in carbon sequestration benefits

TABLE 1 Methodologies for estimating carbon sinks in green spaces.

Research scale	Measurement method	Main technologies	Scope	Main indicators	Advantages	Disadvantages
Macroscopic scale	Sample Plot Measurement	Biomass method, Saving method, Biological inventory method	Large-scale forests	Biomass, carbon content, diameter at breast height*etc.*	High accuracy	High cost of data surveys; destructive to samples, unsustainable observations
	Micro-meteorological method	Eddy Covariance Measurements	Large-scale sample plots	Meteorological data	Intuitive observation of the time dynamics of greenfield carbon sinks	Highly influenced by near-surface atmospheric and topographic conditions; difficult to relocate observatories
	Model Estimation method	CITYGREEN	Small or medium scale green spaces	Vegetation information, site information, climate characteristics	Simple and convenient, with many considerations	Different algorithms between models; differences in modeled vegetation parameters and study area parameters
		I -TREE				
		NTBC				
		Pathfinder				
	Remote Sensing method	GIS、RS*etc.*	Large-scale green spaces	Meteorological, soil, and green space ecological indicators	Results are suitable for relative comparisons	Neglect of ecological differences among tree species
Micro scale	Assimilation method	Portable Photosynthesis System	Plant monocultures, small-scale green spaces	Plant physiological data such as net photosynthetic rate, leaf area index*etc.*	Fast estimation of carbon sequestration on a large scale	Results are highly influenced by the experimental environment, and final results are variable

among different plant species result in two-dimensional indicators that may not fully reflect the actual carbon sequestration benefits of urban green spaces. Assimilation method is the most accurate way to quantify the benefits of plant carbon sequestration, but its results may include large errors owning to experimental weather fluctuations. Moreover, scattered distributions of tree species in the experiment require a long period of time, resulting in limitations of labor dependence. The assimilation amount method is only for single plant scale, so that extensive sample plant data should be carried out when facing the large-scale urban green spaces.

3 Proposal of a prediction method for photosynthetic rate

Existing macroscopic studies, except for assimilation quantities, are limited to estimating carbon sinks and stocks for the current green space as a whole. They are unable to quantify and compare the carbon sinks of individual plants within these green spaces. Therefore, the relevant results and findings are of limited significance in providing guidance on construction of urban green spaces. The assimilation method is the most commonly used and accurate method for studying individual plant carbon sequestration. The results can guide the subsequent planning of tree species in urban green spaces. However, the assimilation method is greatly influenced by weather conditions such as light and temperature, and the results under different weather conditions are not comparable. Therefore, ongoing research should explore more convenient and precise measurement methods.

There have been some studies to utilize a photosynthesis model from natural green spaces at similar latitudes to simulate carbon sequestration through photosynthesis (Soegaard and MLler-Jensen, 2003; Helfter et al., 2010). However, results from non-urban green spaces may not be applicable to urban green spaces due to environmental disparities. Moreover, it is also revealed that plant leaf nitrogen concentration (N) is positively proportional to its net photosynthetic rate and leaf area (Mu and Chen, 2021). Since leaf nitrogen measurements require less time and can be amplified to regional and global scales by satellite sensors (Knyazikhin et al., 2012), there are good potentials to use leaf nitrogen concentration as an indirect estimate of photosynthetic carbon sequestration (Giacomo et al., 2005). However, measurements of leaf nitrogen should be conducted in the laboratory and is not suitable for experiments involving a large variety of tree species. A novel approach based on spatial and temporal dynamic analysis was proposed to study the carbon sequestration and oxygen release capacity of tree species (Chen, 2020). This approach reduces the error of the results due to the difference in experimental time and geographical area. However, the indicators required in this method include not only conventional net photosynthetic rates but also light-response curve, chlorophyll content, etc. Although the data accuracy is high, the experimental process is complex and therefore not practical for application.

Since the plant photosynthetic rate has some intrinsic relationships with internal and external factors, an estimation model can be established through the regression relationship between the photosynthetic rate and the main factors. The photosynthetic rate of plants is primarily influenced by intrinsic physiological factors of the plant itself and external ecological variations. However, intrinsic physiological factors are not artificially controllable and can only be simulated and estimated by altering the experimental environment. The annual variation in plant photosynthetic rates is predominantly driven by changes in

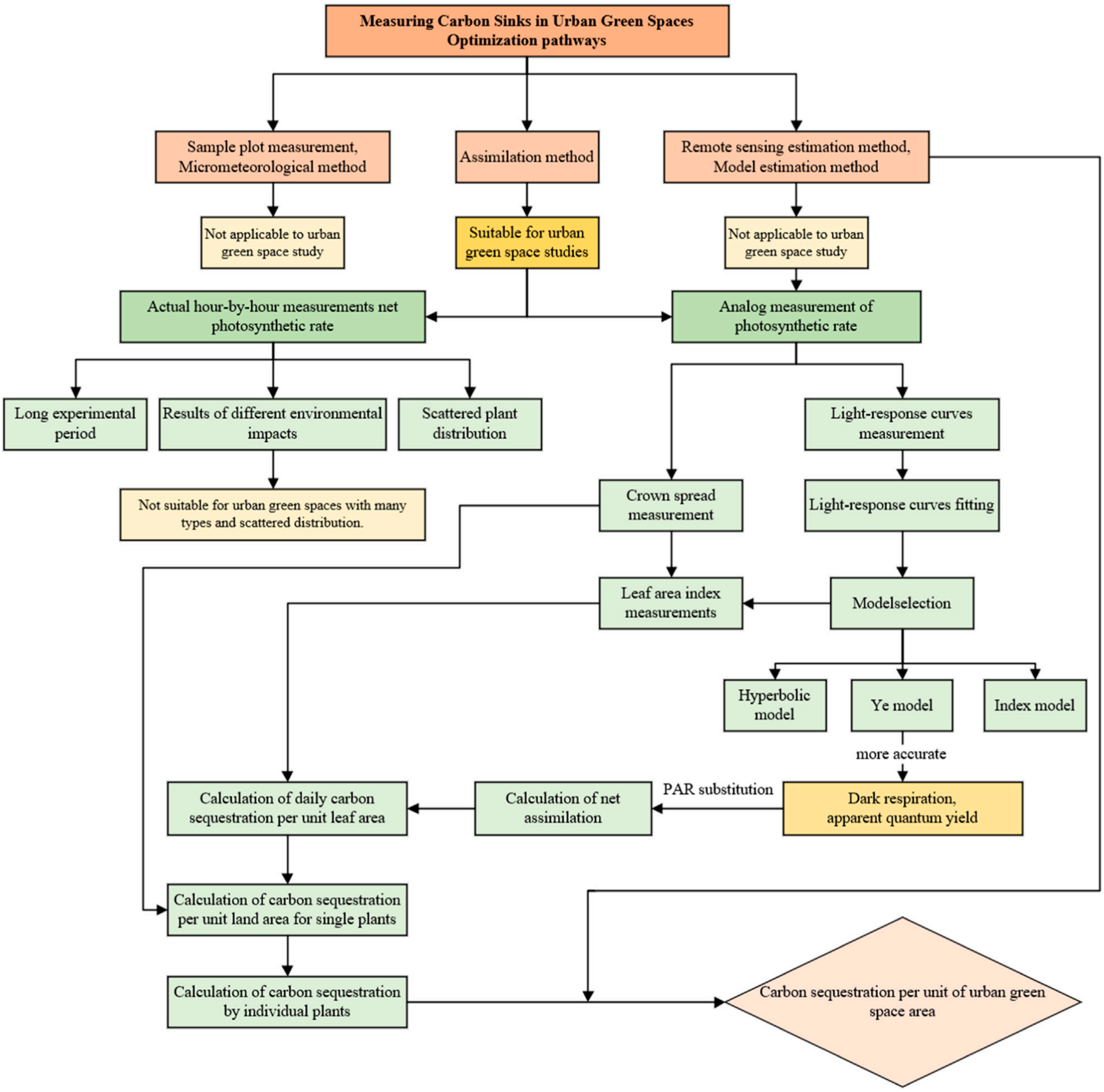

FIGURE 4
Optimization of technical routes.

temperature and light intensity associated with seasons. At diurnal scales, the variation is primarily determined by changes in photosynthetically active radiation (PAR) (Weissert et al., 2017), where in evergreen broadleaf forests, CO_2 concentration decreases with increasing PAR values, and temperature, relative humidity, and CO_2 concentration show insignificant relationships with plant photosynthetic rates. Among these factors, PAR stands out as the most significant factor, while temperature and relative humidity are also greatly influenced by light intensity (Guo, 2012).

Some studies adopt the Farquhar model to fit data and demonstrate an empirical model based on the significant linear relationships between net photosynthetic rate and PAR, deriving (Zhang et al., 2013). Given the maturity of studies on PAR in meteorology, it can be calculated from meteorological observation station data. Accordingly, PAR can be derived as a singular influential factor for predicting plant photosynthetic rates, serving as the basis for a photosynthetic rate prediction model. Specific methods include manual control of light intensity in the leaf chamber, using the light control accessory of the Photosynthesis Measurement System (PMS) to measure the photosynthetic rate of the plant at different light intensities, in order to establish a regression relationship. Typically, existing studies show that there is a significant correlation between the test results of artificially controlled light intensity and actual light intensity under different light geographic conditions (He, 2010). Therefore,

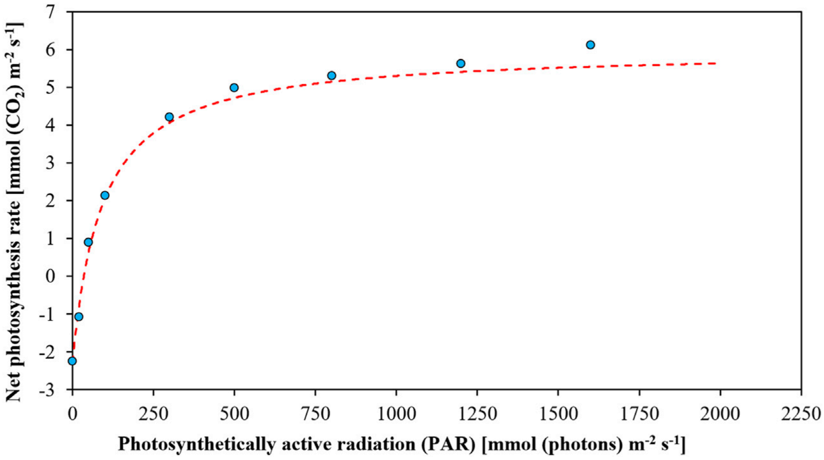

FIGURE 5
The light-response curve to demonstrate the relationship between net photosynthesis rate and photosynthetically active radiation (PAR).

this approach can obtain the photosynthetic rate estimation model through a short testing time, which solves the problems of long hourly testing cycle and distinct results in different testing environments. As a result, this paper proposes to simplify the calculation of plant carbon sequestration benefits by establishing a predictive model through the regression relationship between photosynthesis rate and PAR (Figure 4).

3.1 Modeling

The relationship between net photosynthesis rate and PAR can be described by the net photosynthesis-light response curve which refers to the tendency of the photosynthetic rate of plant leaves to change with the change in the PAR intensity when other environmental conditions are kept unchanged (Figure 5). The light response curves are mainly derived by fitting the photosynthetic rate values exhibited by the plants at different levels of light intensity. In essence, the light response curves show a functional relationship between the photosynthetic rate and light intensity, so that it can be used as a model to predict photosynthetic rate.

Many models have been used to fit net photosynthetic light-response curves, such as exponential model (Eq. 1) (Bassman and Zwier, 1991), rectangular hyperbolic model (Eq. 2) (Baly, 1997), non-rectangular hyperbolic model (Eq. 3) (Gates, 1977; Hardwick, 1977), and mechanistic model (Eq. 4) (Ye, 2007). These models describe photosynthetic physiology and can reasonably analyze the whole process of the light response curve so that they are capable of obtaining accurate data and fitting curves with high reliability. However, there are no models suitable for all situations. For instance, the data fitted by the non-rectangular hyperbolic model and the exponential model are more in line with actual data, but the prediction results of the mechanistic model were more accurate and realistic (de Lobo et al., 2013). Accordingly, the mechanistic model was later modified and simplified as Eq. 5 (Ye et al., 2013). In practice, the fitting can be done by Ye's photosynthetic computational model and the computational model built upon Microsoft Excel (de Lobo et al., 2013).

$$Pn = P\,max\,(1 - e^{-\frac{\alpha I}{Pmax}}) - Rd \tag{1}$$

$$Pn = \frac{\alpha I Pmax}{\alpha I + Pmax} - Rd \tag{2}$$

$$Pn = \frac{\alpha I + P\,max - \sqrt{(\alpha I + Pmax)^2 - 4\theta\alpha I Pmax}}{2\theta} - Rd \tag{3}$$

$$Pn = \alpha \times \frac{1 - \beta \times I}{1 + \gamma \times I} \times \left(I - I_{comp}\right) \tag{4}$$

$$Pn = \alpha \times \frac{1 - \beta \times I}{1 + \gamma \times I} \times I - Rd \tag{5}$$

where Pn represents the net photosynthetic rate [μmol (CO$_2$) m^{-2}·s^{-1}], which is the difference between the overall photosynthetic rate and the dark respiration rate of the plant; $Pmax$ is the maximum net photosynthetic rate [μmol (CO$_2$)m^{-2}·s^{-1}]; θ is the curvature of the curve; I is the photosynthetic photon flux density; α is the initial slope of the light response curve at $I = 0$, representing the initial quantum efficiency of the photosynthetic process [μmol (CO$_2$) (photon)$^{-1}$]; Rd is the dark respiration, the amount of carbon dioxide released by the plant in dark [μmol (CO$_2$) (photon)$^{-1}$]. I_{comp} is the light compensation point [μmol (photon)m^{-2}·s^{-1}], and β and γ are adjustment factor.

3.2 PAR value estimation

Solar radiation is the primary energy source of the Earth's surface, where the portion of solar radiation that can be utilized by green plants for photosynthesis is defined as PAR, also known as light intensity. PAR serves as the energy source for plant biomass and constitutes a crucial parameter for assessing plant photosynthetic potential (Zhou and Xiang, 1996). The current measurement methods for PAR include the energy system (W·m^2) for determining PAR illuminance (Q$_{PAR}$) and the quantum system (μmol·m^{-2}·s^{-1}) for determining PAR density (U$_{PAR}$). The PAR density is also known as the photosynthesis photon flux density (PPFD), presenting the number of photons incident on a unit surface per unit time (Sun et al., 2017). Under illumination by light sources with different spectral structures, the ratio between leaf photosynthetic rate and photosynthetically active quantum flux density exhibits minimal variation (McCree, 1972). Compared with the energy system, the quantum system for determining the photosynthetically active quantum flux density U_{PAR} is more reasonable. Therefore, quantum measurement systems are increasingly prevalent in fields such as agriculture and ecology.

However, U_{PAR} depends on wavelength and therefore cannot be derived directly from solar irradiance (Wang et al., 2021). Instruments specifically designed for directly measuring the light quantum flux U_{PAR} are not widespread, and most meteorological stations lack regular observation platforms for PAR. As a result, U_{PAR} is generally calculated in an indirect way, such as using UV-visible band fluxes to estimate (Sun et al., 2017), or using meteorological datasets to develop models (García-Rodríguez et al., 2021). On the meteorological conversion, the conventional unit for solar radiation in meteorological parameters is horizontal total radiation ($W{\cdot}m^{-2}$), which can be quantitatively converted into light quantum flux ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) (Wang et al., 2005). More importantly, meteorological research indicates a stable proportion of PAR in total solar radiation. Therefore, the meteorological conversion relationship involves calculations of the photosynthetically active coefficient and quantum conversion coefficient, which are usually calculated by the following empirical formula (Zhou et al., 1984).

$$Q_{PAR=}\eta Q \tag{6}$$

$$U_{PAR} = \mu Q_{PAR} \tag{7}$$

$$U_{PAR} = \mu\eta Q \tag{8}$$

where η is the photosynthetic efficiency coefficient, representing the proportion of photosynthetically active radiation energy in the total solar radiation; μ is the quantum yield indicating the number of quanta per unit photosynthetically active radiation energy, with units of $\mu mol{\cdot}J^{-1}$; Q is the total horizontal solar radiation flux, measured in $W{\cdot}m^{-2}$; Q_{PAR} is the photosynthetically active radiation intensity, measured in $W{\cdot}m^{-2}$; U_{PAR} is the photon flux of photosynthetically active radiation, measured in $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$.

The current annual average value of η in Eq. 6 is between 0.409 and 0.477 worldwide (Akitsu et al., 2022). Observational studies indicate that η is influenced by both astronomical and meteorological factors. Long-term continuous synchronous observations of Q and PAR in locations such as Beijing, Yantai, and Zhengzhou revealed the stability of η values (Wang and Shui, 1988). A suitable calculation formula for plains was derived as $Q_{PAR} = 0.42$ Q, where $\eta = 0.42$. Subsequent research on cities like Chengdu, Kunming, and Guangzhou yielded similar conclusions (Wang and Shui, 1990), and other scholars found similar results that η is 0.39 ± 0.04 (Zhou et al., 1984). Consequently, the quantum conversion coefficient for China can be established as 0.42.

There is no systematic climatological research result about the value of the quantum conversion factor μ. McCree concluded $\mu = 4.57\ \mu mol\ J^{-1}$ (McCree, 1972), but the value of μ in Eq. 7 is inconsistent in different regions of China, and at present the intermediate value is $4.55\ \mu mol\ J^{-1}$ (Dong et al., 2011) so based on Eq. 8 that the conversion relationship between Q and PAR is $U_{PAR} = \mu \times \eta = 4.55 \times 0.42\ Q = 1.911\ Q$.

3.3 Experimental procedure

Although no study has found a significant relationship between plant net photosynthetic rate and its size (Weissert et al., 2017), it is advisable to select healthy tree species with a planting age between 3 and 10 years for experiment. Since it is always challenging to measure the height of large deciduous trees using *in-situ* methods, auxiliary measurements are often carried out by tools such as cherry pickers and tower cranes (Chen et al., 2003; Zhao et al., 2008). However, this approach is applicable to only a few tree species with short measurement cycles. Given the diverse and scattered distribution of plant species in urban green spaces, as well as constraints posed by topography, the feasibility of this method is low. Alternatively, *in vitro* measurements are generally adopted. Whilst the photosynthetic rate of some plants may slightly decrease shortly after detachment, most tree species exhibit a high and stable photosynthetic rate within the first hour after detachment (Tang and Wang, 2011). As a result, the light response curves of plants measured within the first hour of leaf detachment can largely represent *in situ* measurements.

Currently, the main method for *in vitro* measurements is to restore the water supply to detached branches and leaves to alleviate water stress, thereby restoring their photosynthetic capacity to the *in situ* level (Qiang et al., 2017). Typically, plant branches are cut and immediately immersed in water, and the cut surface is maximized by making a second diagonal cut in the water, and subtracting excess foliage from the branches will reduce water loss (Xu, 2006). After measurements, the mechanism model of light response through photosynthesis such as leaf floating was adopted to fit formula (Ye et al., 2013), with the initial values of each parameter: $\alpha = 0.06$, $\beta = 0.002$, $\gamma = 0.01$, and $Rd = 1$, and the limiting range of $0 < \alpha < 0.1$, $0.002 < \beta < 0.01$, $0.01 < \gamma < 0.03$, and $0 < Rd < 3$. The measurement steps are as follows:

(1) Prune the middle branches of the plant canopy by pruning shears, and place the cut ends into water quickly. Afterwards, make another diagonal cut approximately 3 cm from the initial cut to increase the water absorption area of the branches, during which remove the majority of leaves or leaflets from the branches to minimize water loss from detached plant materials.
(2) Select the fifth to seventh mature leaves from the top of the branches and wipe them clean.
(3) Place the leaves in a controlled light chamber with an LED red-blue light source, and tight up the chamber to ensure airtightness.
(4) Install a CO_2 injection system and set it to the same average concentration as the test area.
(5) Adjust the light intensity in the chamber to $1{,}600\ \mu mol\ m^{-2}{\cdot}s^{-1}$ using the red-blue light source, and expose the leaves to internal illumination for approximately 10 min for activation.

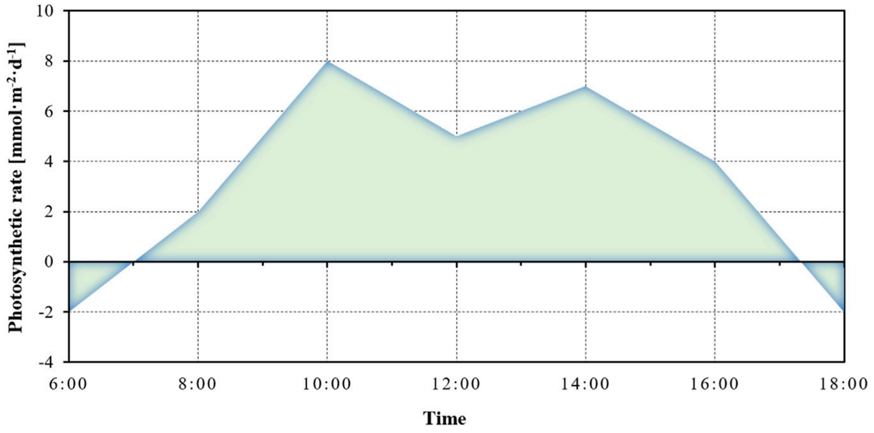

FIGURE 6
Daily assimilation of plant photosynthesis.

(6) Control the light intensity sequentially to 1,600, 1,200, 800, 500, 200, 100, 50, 20 and 0 μmol m^{-2}·s^{-1} using the light intensity controller. After adjusting the light intensity, allow the leaves to adapt for stabilizing about 3 minutes before recording the photosynthetic rate.

3.4 Calculation

3.4.1 Calculation of net assimilation

For the daily assimilation, it is defined as the area enclosed by the net photosynthetic rate curve and the time (Figure 6). The net assimilation refers to the difference between the organic substances formed during photosynthesis and those consumed during respiration within a unit of time, and this value is directly proportional to plant photosynthetic capacity and carbon sequestration (Chen, 2020). Assuming that the PAR is 10 h per day, the net assimilation of the plant on the day of measurement can be calculated by Eq. 9 (Han, 2005).

$$P = \sum i\left[\frac{(P_{i+1} + P_i)}{2} \times \frac{(t_{i+1} - t_i) \times 3600}{1000}\right] \tag{9}$$

where P represents the net assimilation total per unit leaf area determined on the measurement day, with units of mmol·m^{-2}·s^{-1}; P_i denotes the instantaneous photosynthetic rate at the initial measurement point, and P_{i+1} represents the instantaneous photosynthetic rate at the $i+1$ measurement point, both in units of μmol·m^{-2}·s^{-1}; t_i is the instantaneous time at the initial measurement point, t_{i+1} is the time at the $i+1$ measurement point, and $t_{i+1} - t_i$ is the test interval time, measured in hours [h]; j signifies the number of test repetitions; 3,600 corresponds to the conversion factor from seconds to hours; 1,000 is the conversion factor between mmol and μmol.

3.4.2 Daily carbon sequestration per unit leaf area of plants

Daily carbon sequestration per unit leaf area refers to the amount of carbon dioxide absorbed by a single leaf area in a unit of time, commonly expressed in kg·m^{-2}·a^{-1}. The nocturnal respiratory release of carbon dioxide is generally calculated as 20% of the assimilation amount during the day. The calculation of the daily carbon sequestration per unit leaf area, based on the reaction equation of photosynthesis ($CO_2+4H_2O \rightarrow CH_2O+3H_2O+O_2$), is expressed by Eq. 10.

$$W_{co2} = P \times (1 - 0.2) \times \frac{44}{1000} \tag{10}$$

where 44 represents the molar mass of carbon dioxide; W_{co2} denotes the mass of CO_2 sequestrated per unit area of leaves [g·m^{-2} d^{-1}]. Based on Eqs 5, 9, 10, 11 can be derived for predicting the plant-specific carbon fixation per unit leaf area according to PAR.

$$W_{co2} = 0.06336 \times \sum i\left[\alpha \times \left(\frac{1 - \beta \times PAR_i}{1 + \gamma \times PAR_i} + \frac{1 - \beta \times PAR_{i+1}}{1 + \gamma \times PAR_{i+1}}\right) - 2Rd\right] \tag{11}$$

where PAR_i represents the instantaneous PAR at the initial moment [μmol·m^{-2}·s^{-1}]; PAR_{i+1} represents the PAR at the next moment [μmol·m^{-2}·s^{-1}].

3.4.3 Carbon sequestration per unit land area by individual plants

Carbon sequestration per unit land area by an individual plant, also known as daily carbon sequestration per unit coverage area, represents the mass of carbon dioxide sequestrated by all leaves on the entire projected area of a landscaping plant in a unit of time, as described by Eq. 12.

$$Q_{co2} = LAI \times W_{co2} \tag{12}$$

where LAI is the leaf area index of a single plant; Q_{co2} is the amount of CO_2 fixed per unit of land area per day by a single plant.

Most previous studies regarded the carbon sequestration benefits of plants as total biomass, including leaves, stem diameter, roots, and rhizomes. This benefit is often determined by measuring the absolute greenness of a certain area (Profous et al., 1988). However, the photosynthesis intensity primarily depends on the effective surface area of leaves involved in photosynthesis. Therefore, the LAI, the total

TABLE 2 Estimation methods for leaf area index of green urban vegetation.

Measurement methods	Main technologies	Main indicators	Advantage	Disadvantage
Leaf area Method	Digital software, Portable leaf are meter, standard branch method	Single leaf area, single plant leaf volume	Relatively accurate results	Complex experimental methods and individual differences in leaf volume and leaf area
Photogrammetry	Plant canopy analyzer instruction	Forest crown clearance score	Simple and convenient, relatively accurate results	Discrepancies may exist between strains
Leaf area regression model	Mathematical model	Crown height, shade coefficient of crown width	Low cost, simple, obtaining results quickly	Individual differences may exist in generic formulas

plant leaf area per unit land area as a multiple of land area, is an important indicator reflecting the density of tree leaves and plant carbon sequestration capacity. A higher LAI indicates a greater leaf area per unit land area and a higher degree of leaf overlap (Ma et al., 2023). Plant growth and carbon sequestration increase with the LAI. The LAI determination can be influenced plant growth period and plant condition. In actual applications, three methods such as leaf area method, instrument measurement method, and regression equation method are commonly employed (Table 2).

The leaf area method calculates the average area of individual plant leaves using devices like portable leaf are meter. The standard single-leaf area should be obtained using the standard branch method based on the entire leaf quantity of an individual plant. Photogrammetry can directly calculate the LAI of plants using plant canopy analyzer instruction, typically selecting the average of the LAI values from multiple directions as the final LAI. The regression model is derived based on physiological indicators such as DBH and tree height (TH) to derive the total leaf area of individual plants (Goude et al., 2019). For example, the urban tree leaf area regression model for Chicago, which was developed on information based on multiple species, ages, DBH and TH, is generalizable because the overall error due to the parameters is not too large, and has been widely used in other regions as well (Mcpherson et al., 1994). Regression models specific to different regions have also been developed based on local tree species characteristics. For example, the LAI of 40 common garden plants in Beijing was determined by a canopy analyzer and a regression model of LAI was established based on the relationship between crown width, DBH, plant height and LAI (Shen, 2007).

3.4.4 Daily carbon sequestration of individual plants

Daily carbon sequestration of individual plants refers to the total amount of carbon dioxide sequestration by an individual plant within a daily time, as described by Eq. 13.

$$M_{co2} = W_{co2} \times S(LAI \times C) \tag{13}$$

where W_{co2} represents the mass of CO_2 sequestrated per unit leaf area of an individual plant [g/d]; S denotes the total leaf area of an individual plant; C is the plant canopy area (vertical projection area).

3.4.5 Daily carbon sequestration per unit of green space area

Urban green space is composed of a large number of individual plants so that daily carbon sequestration per unit of green space area can be calculated by the daily carbon sequestration of each individual plant within the unit of green space. Total carbon sinks in urban green spaces can be quantified using the methodology of plant communities, as expressed by Eq. 14 (Sultana et al., 2021).

$$C_{Sij} = C_{Aij} \times N_{Sij} \tag{14}$$

where i represents the specification; j is the tree species; C_{Sij} is the sum of daily carbon sequestration per unit of green space area; C_{Aij} is the daily carbon sequestration by a single plant of the type; N_{Sij} is the number of plants of the type.

4 Discussion

4.1 Significance of accounting carbon sinks in urban green spaces

It is a consensus embraced by governments and organizations worldwide that urban green spaces are efficient natural carbon sinks and a crucial strategy for mitigating climate change. The loss of carbon sinks due to built-up area increase during urbanization should be compensated by urban green spaces (Nowak et al., 2013). In this context, the carbon offsetting capacity (COC), the ratio between carbon emissions from human activities and the carbon sink of green spaces, has been attracting attention (Chen, 2015). Accordingly, quantitative studies on urban green space carbon sinks not only elucidate their paramount significance for cities but also clarify their ecological value, providing a foundation for subsequent management endeavors. At present, research mainly focuses on the indirect quantification of carbon sinks, holding crucial implications for investigating carbon offset capabilities, as well as ecological and economic benefits. In comparison and more importantly, directly quantifying the individual carbon sequestration capacity of urban green space allows the identification of locally suitable high-efficiency carbon sequestration plants, which can guide future urban green space construction and maximize ecological benefits (Table 3). Despite urban green spaces contributing a fraction of carbon sink capacity compared to urban carbon emissions, appropriate design and management of vegetation, as the primary component of urban green spaces, can significantly enhance future carbon sink capacity. This enhancement must be based

TABLE 3 Comparison of research methods for calculating carbon sinks in urban green spaces.

Research methodology	Measurement method	Estimation method	Object	Current significance	Future significance
Sample Plot Measurement	Indirect	Indirect	Current Green Space	Quantifying ecological benefits	——
Model Estimation Method	Indirect	Indirect			——
Remote Sensing	Indirect	Indirect			——
Micro-meteorological method	Indirect	Indirect			——
Assimilation	Direct	Direct			Guidance for future tree selection

on an understanding of differences in carbon sequestration benefits among various plant species. In addition, the ecological benefits of plants, such as cooling and fire prevention, hold equal importance in climate change mitigation (Murray et al., 2018; Liu X. et al., 2023). In future research, integrating studies on plant carbon sequestration with quantifications of other ecological benefits may prove more advantageous for the sustainable development of cities.

4.2 Trends in research methods for measuring greenfield carbon sinks

Methodologies for quantifying carbon sequestration in urban green spaces exhibit a diverse trend, and existing methods tailored to different scales and types of green spaces are predominantly concentrated in fields such as forests, grasslands, and agricultural areas. Concurrent studies are exploring the integration of various research methods. For instance, employing the accumulation method principle, directly utilized ArcGIS to estimate the carbon sequestration in Russian forests (Malysheva et al., 2018) and used the IUEMS carbon sequestration and oxygen release model to study forest carbon sequestration in the Qinling Mountains based on net ecosystem productivity (Ma et al., 2022). The CASA model was adopted to estimate the carbon sinks of greenfield vegetation in some major cities in China based on satellite images, meteorological data and vegetation data (Xu et al., 2023), or extracting plant species and leaf area indices from large green spaces by satellite and RS correlation techniques to estimate carbon sink benefits (Johnson et al., 2023). In future, more fusion methods should be explored for simpler and more accurate studies.

4.3 Limitations of the photosynthetic rate estimation

To address the challenges of experimental requirements in the assimilation method, this study proposes a method by establishing a model for estimating photosynthetic rate based on light-response curves. This involves measuring the net photosynthetic rate of plants under different levels of light intensity and utilizing mechanistic model of light-response of photosynthesis to fit the light -response curve. The actual hourly PAR is incorporated to simulate the plant's hourly net photosynthetic rate on corresponding dates. The carbon sequestration of plants can be finally quantified using the formula for calculating plant carbon sequestration. This standardized external environment setting allows for the carbon sequestration comparison among different plants under the same conditions, enabling more accurate selection of plants with high carbon sink. The study presents controlled adjustments to the light intensity environment, CO_2 concentration and other conditions in the leaf chamber of the photosynthesis measurement instrument to ensure a consistent experimental environment. Although light intensity and atmospheric CO_2 concentration have the most significant impact on plant photosynthetic rates (Xiao et al., 2019), other external factors can also influence photosynthetic rates. Therefore, in future experiments, there is a need to control the other conditions to make the data more accurate.

There have been many models for net photosynthesis-light response curve fitting, and studies have shown that there are uncertainties in the fitting models (Fang et al., 2015). Moreover, the calculation results of some data of these models may be out of the normal range, this study, to use the light response curve fitting model, follows the mechanism model of photosynthesis response to light. It is a modified model for the rectangular hyperbolic model, having some advantages compared with previous models, and more accurate and real data can be obtained when calculating α. However, the data such as $P_{\max}$ will be out of the normal physiological range under some circumstances (de Lobo et al., 2013), which should be overcome to increase the accuracy of the results in the future research. Finally, although the predicted net photosynthetic rate values based on the light response curve exhibit a strong correlation with the actually measured values, this does not mean that the results of the two experimental methods are consistent. The photosynthetic rate estimation method based on the light response curve is only applicable to preliminary research on quantifying carbon sequestration in a large number of urban green spaces. More precise carbon sequestration data requires actual hourly measurements.

4.4 Future research

Quantifying carbon sink in urban green spaces is crucial for guiding future urban green space planning and management efforts. Therefore, research should not only concentrate on the direct carbon sink capacity of plants but should also comprehensively explore aspects such as the reduction in carbon emissions, self-generated carbon emissions, and factors influencing carbon sink. This will provide clearer paths for the future construction of urban green space, and help to promote the limited urban green space to play the greatest carbon sink benefits. Regarding carbon emissions, urban green spaces, through shading and transpiration, can lower the overall temperature of the city, thereby reducing building energy consumption and indirectly decreasing urban carbon emissions (Dong and He, 2023). Studies indicate that trees in urban centers indirectly absorb more CO_2 than they do directly (McHale et al., 2007). Concerning self-generated carbon emissions, although urban green space vegetation can sequester carbon through photosynthesis, the carbon emissions generated throughout its entire lifecycle, including production, transportation, and management can offset a portion of the carbon sequestration (Park et al., 2021). Deducting the total carbon emissions from the overall carbon sequestration quantity is meaningful for understanding the net carbon sequestration benefits of plants.

On carbon sinks, their influencing factors can be categorized into plants themselves, and planning and design. Regarding plants, indicators such as LAI, size, tree age, tree diameter, and tree height have a significant impact (Othman et al., 2019; Shadman et al., 2022). Moreover, the amount of carbon sequestered by plants varies geographically. Native plants can also show better carbon sequestration efficacy given their local adaptability that means small carbon emissions from maintenance management (Wang et al., 2015). Additionally, past research has predominantly focused on trees and shrubs, neglecting the substantial carbon sink role played by extensive lawns in urban green spaces (Amoatey and Sulaiman, 2020), thus necessitating a quantitative study. On planning and design, plants show different carbon sink abilities with different planting designs. Quantifying the carbon sink capacity variation under different planning and design schemes is important to provide guidance for optimization. Planting density of plant communities had a significant positive relationship with their carbon sequestration (O'Donoghue and Shackleton, 2013), but excessively high density can have opposite effects (Mexia et al., 2018). The proportion of trees and shrubs, plant community hierarchy, biodiversity and vegetation spatial types also significantly affect the carbon sink capacity. Meanwhile, there is a spatial correlation between human activities and greenfield carbon sinks (Dong et al., 2023). On management, digital means can be used to realize the analysis and accurate management of urban green spaces. For example, a digital platform for high carbon sequestering plant communities developed by Python and other programming software in Xi'an provided a scientific guidance for decision-making in plant community design (Wang et al., 2023).

Overall, increasing the carbon sink of green space cannot be only considered in an individual aspect, but should be considered comprehensively from the whole life cycle of plant selection, community design, and maintenance management. However, only from the construction perspective to study the carbon sink of urban green space has a temporary nature. In future, there is a need to study the influencing factors to optimization carbon sink of urban green space so that it can play long-term and better carbon sink benefits. It is also possible to form evaluation standards and systems related to carbon sinks on the basis of carbon sink measurement and quantification, so as to provide a practical basis for evaluating various types of urban green areas.

5 Conclusion

Carbon sink function is one of the most important ecological benefits of urban green space. The associated quantification is not only important for carbon sink measurement, but also important for the future construction of urban low-carbon green space. In this study, we clarified the existing green space carbon sink assessment methods, divided them into macro and micro scales, and analyzed their advantages and disadvantages. It is found that macroscopic methods can accurately estimate the carbon sink benefits of large-scale green spaces, but they cannot be completely applied to urban green spaces and cannot distinguish the carbon sequestration benefits of individual plants. The assimilation method as a research method of carbon sequestration by individual plants can make up for these shortcomings. The assimilation method is more favorable for quantifying the carbon sequestration benefits of individual plants in urban green space. This method can better support the construction of low carbon green space, and can be combined with other tools to accurately estimate carbon sequestration benefits of large-scale green space. However, the assimilation method is affected by the weather and the data comparability is limited by measurement conditions. Therefore, this study proposed to measure net photosynthesis-light response curves in a uniform experimental environment, estimate the net photosynthesis rate by using the photosynthesis-photorespiration-response model of leaf drift as a single-factor variable, and finally calculate carbon sequestered by plants. Moreover, future studies should in-depth explore plant indirect emission reduction benefits and the whole life cycle carbon emissions, and explore the impact of different plant community design and plant indicators on the carbon sink of urban green spaces. Overall, this paper is important to provide a good methodological reference for quantifying carbon sinks in urban green spaces.

Author contributions

LD: Funding acquisition, Methodology, Resources, Supervision, Writing–review and editing. YW: Conceptualization, Investigation, Writing–original draft. LA: Funding acquisition, Writing–review and editing. XC: Methodology, Writing–review and editing. YL: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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