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RECEIVED 19 December 2025

REVISED 22 April 2026

ACCEPTED 04 May 2026

PUBLISHED 29 May 2026

CITATION

Chen C, Anna Z, You X and Jingyun W
(2026) Carbon sequestration capacity of
roadside vegetation along a high-traffic
expressway in central China.
Front. Environ. Sci. 14:1771385.
doi: 10.3389/fenvs.2026.1771385

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Carbon sequestration capacity of roadside vegetation along a high-traffic expressway in central China

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Road transportation is a major contributor to global greenhouse gas emissions, yet roadside vegetation along expressways can serve as an effective carbon sink. However, systematic assessments of the carbon sequestration potential of roadside plants in central China remain limited. This study evaluated the carbon sequestration capacity of vegetation along a 158 km section of the G4 Expressway in Hubei Province. Field measurements of net photosynthetic rate and leaf area index were conducted for 31 tree species, 18 shrub species, and four herbaceous combinations. Carbon sequestration was quantified using assimilation and biomass methods, and species were classified by efficiency via cluster analysis. The results show that the total annual carbon sequestration of the studied vegetation reaches approximately 33,165 tons, with trees contributing 57%, shrubs 37%, and herbs 6%. Trees with high leaf area indices—such as *Pterocarya stenoptera* (128.10 g m⁻².d⁻¹) and *Liquidambar formosana* (126.41 g m⁻².d⁻¹)—exhibit superior carbon sequestration per unit land area, while among shrubs, *Photinia × fraseri* (73.11 g m⁻².d⁻¹), *Nerium oleander* (49.90 g m⁻².d⁻¹), and *Hibiscus mutabilis* (50.62 g m⁻².d⁻¹) demonstrate the highest efficiency. Cluster analysis further categorizes species into high, medium, and low carbon sequestration groups, providing a clear basis for species selection. The findings underscore that photosynthetic efficiency and canopy structure are more critical for carbon sequestration performance than planting quantity alone. This study recommends prioritizing native species with high photosynthetic efficiency and implementing a multi-layered “tree–shrub–herb” configuration tailored to site-specific conditions. The results provide a scientific basis and practical guidance for low-carbon expressway greening in central China and offer a reference framework for regions with similar climatic conditions.

KEYWORDS

carbon sequestration, expressway, leaf area index, roadside vegetation, vegetation configuration

1 Introduction

Global climate change poses a major challenge to human society, fundamentally driven by the continuous increase in atmospheric greenhouse gas concentrations caused by human activities (Masson-Delmotte et al., 2018). Reducing greenhouse gas emissions, particularly carbon dioxide (CO₂), has become a shared and imperative goal for mitigating the impacts of climate change (Gillingham and Stock, 2018; Herzog et al., 2000). Within global carbon emissions, the transportation sector has emerged as one of the primary contributors to

global climate change (Ferrer and Thome, 2023). In 2019, global greenhouse gas emissions from transportation reached 8.7 billion tonnes of CO₂ equivalent (compared to 5.0 billion tonnes of CO₂ equivalent in 1990), accounting for 23% of global energy-related CO₂ emissions. Within the transportation sector, road transport is responsible for 70% of these emissions, while rail, shipping, and aviation account for 1%, 11%, and 12%, respectively (Shukla et al., 2022). From 2010 to 2019, emission rates from energy supply and industry showed relatively low declines, whereas emissions from transportation maintained a consistent annual growth rate of approximately 2%. It was also responsible for 8.7 Gt CO₂-eq that year, estimated to grow within the 16%–50% range by 2050 (Bashmakov et al., 2022).

Among various modes of transport, road transportation consumes the most energy and generates the largest share of carbon emissions. With economic growth and the increasing number of vehicles, this energy consumption is expected to continue rising (Chen et al., 2017). It is generally recognized that there are three primary approaches to reducing greenhouse gas emissions (Schrag, 2007): (1) decreasing the use of fossil fuels; (2) adopting low-carbon or carbon-free energy sources; and (3) capturing or sequestering CO₂ either at the source or from the atmosphere.

A fundamental and critical issue in the global ecosystem and carbon cycle is the “source” and “sink” of greenhouse gases (Watson et al., 1992). Within the road environment, a substantial number of trees absorb significant amounts of carbon dioxide from the atmospheric carbon pool through photosynthesis, which plays an important role in reducing greenhouse gas emissions from the transportation sector (Da Silva et al., 2010; Fu et al., 2019). Therefore, it is essential to study the carbon sequestration capacity of roadside vegetation. Based on this capacity, carbon sequestration can be enhanced by increasing green cover and adjusting plant species (Ament et al., 2014; Xiang-Yan et al., 2014). Researchers have analyzed tree height and crown width data of three street tree species in Tshwane, South Africa, from 2002 to 2008, and projected their total carbon uptake over the next 30 years (Stoffberg, 2010). David J. Nowak analyzed carbon storage and exchange rates based on tree cover data from ten U.S. cities (Nowak and Crane, 2002). Some scholars have determined the carbon sequestration capacity of plants by analyzing the relationship between physiological traits, soil properties, and plant carbon sequestration (Bai and Zhang, 2025). Another study investigated the carbon sequestration capacity of herbaceous plants along roads in northern China (Na et al., 2023). Current research on roadside vegetation configuration mainly focuses on landscape effects, ecological sensitivity, and slope protection. Although some studies have assessed the carbon sequestration capacity of roadside vegetation along expressways in eastern China (Fu et al., 2019), comprehensive evaluations of the carbon sequestration potential of roadside vegetation across China remain relatively scarce.

This study investigates the carbon sequestration capacity of roadside vegetation along a 158 km section of the G4 Expressway in Hubei Province, central China. A total of 50 woody species (31 trees and 18 shrubs) and four herbaceous mixtures were selected for analysis. Based on field measurements of net photosynthetic rate and leaf area index, we quantified carbon

sequestration per unit leaf area and per unit land area. Cluster analysis was employed to classify species by carbon sequestration efficiency, aiming to identify high-potential species. The findings provide a scientific basis and practical guidance for optimizing roadside vegetation configuration to enhance carbon sequestration functions in highway systems.

2 Materials and methods

2.1 Study area

This study focuses on a section of the G4 Expressway, one of the busiest highways in central China (Figure 1). The investigated segment spans from Dawu to Caidian within Hubei Province, covering a total length of 158 km, with a daily traffic volume of up to 56,000 vehicles. The region has a subtropical continental monsoon climate, featuring four distinct seasons, ample rainfall, warm and humid conditions, and sufficient sunshine. The mean annual temperature ranges between 15.5 °C and 16.5 °C, with annual sunshine duration of 2020–2190 h. Annual precipitation varies from 1040 to 1230 mm, of which about 70% occurs from April to September.

To minimize discrepancies in carbon sequestration estimation caused by regional variation, sampling points were evenly distributed along the entire expressway. Sampling ranges were established at 30 km intervals, with sites located in service areas and green belts at expressway interchanges. In accordance with expressway landscape design requirements, different plant categories are employed in distinct zones.

2.2 Carbon sequestration calculation

2.2.1 Measurement of net photosynthetic rate

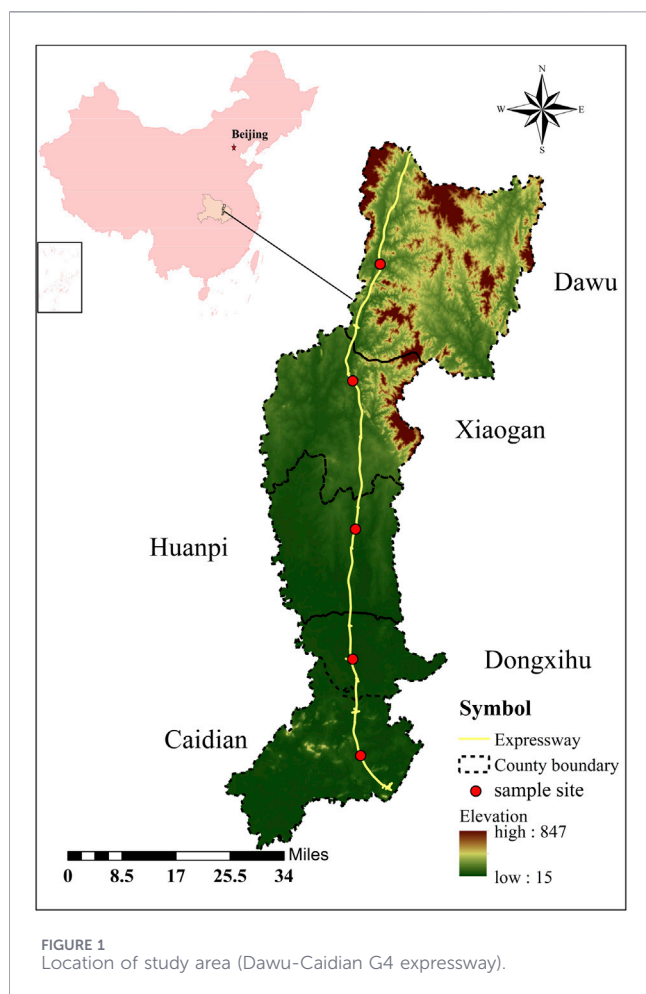
Leaf photosynthetic rate was measured using a Li-6400 portable photosynthesis system. Measurements were taken every 2 hours from 8:00 to 18:00 under natural light conditions. Three healthy plants of similar age, height, and crown size were selected for measurement. From each plant, four well-grown current-year branches facing east, south, west, and north were chosen. On each branch, a healthy, disease-free leaf with consistent orientation was selected, and 3–6 instantaneous photosynthetic rate readings were recorded per leaf as replicates.

The diurnal net photosynthetic rate of the plants was measured in this study. Considering the importance of dark respiration and its seasonal variation, the daily net carbon sequestration of plants was calculated using Equation 1:

$$T_{\text{carbon sequestration}} = \sum_{i=1}^n (1 - r_i) \times P_{\text{net},i} \times t_i \quad (1)$$

where:

$T_{\text{carbon sequestration}}$ represents the annual carbon sequestration of trees and shrubs; r_i denotes the ratio of nocturnal dark respiration to diurnal net photosynthesis in different seasons, with values of 0.19 in spring and autumn, 0.23 in summer, and 0.07 in winter (Chu et al., 2011); $P_{\text{net},i}$ represents the carbon sequestration derived from



daytime net photosynthesis for a single day in different seasons; t_i represents the number of days in each season.

2.2.2 Assimilation method

The carbon sequestration of trees and shrubs was calculated using the assimilation method (Figure 2). The daily net assimilation per unit leaf area was obtained by measuring the daily net photosynthetic rate per unit leaf area of the plants.

The leaf area index (LAI) is defined as the ratio of the total one-sided leaf area of plants to the ground area they occupy. Specifically, $LAI = \text{Total leaf area of an individual plant} / \text{Projected crown area of that plant}$ (i.e., the ground area). LAI shows a significant correlation with plant height and diameter at breast height (DBH). Previous studies have developed regression models for estimating LAI in different tree species (see Table 1), and comprehensive regression models for trees and shrubs (Equations 2, 3) have also been established (Guo, 2009; Nowak and Crane, 2002). In this study, species-specific regression models were prioritized when available; for species without such models, the comprehensive regression models for trees and shrubs were applied. Cross-validation between the species-specific and comprehensive regression models revealed a mean error of 39.82%. Accordingly, LAI in this study was estimated using regression equations derived from data reported in previous studies.

The comprehensive regression model of LAI is as follows:

$$\text{Trees: } Y_1 = \exp(0.616 + 0.169t_1 + 0.01t_2 - 0.02t_2 \ln t_1) \quad (2)$$

$$\text{shrubs: } Y_2 = 3.079 + 0.135t_3t_4 \quad (3)$$

where, Y_1 represents the predicted actual LAI of trees; t_1 denotes the average crown length of trees; t_2 is the canopy coverage of trees; Y_2 represents the predicted actual LAI of shrubs; t_3 denotes the average crown length of shrubs; t_4 is the canopy coverage of shrubs.

Field data were collected during four seasonal campaigns: March–April 2023 (spring), July–August 2023 (summer), October–November 2023 (autumn), and January–February 2024 (winter). In each sample plot, tree height, crown length, and species-specific canopy coverage were measured. The average height, canopy coverage, and crown length of trees and shrubs were determined using standard quadrats of 10 m × 10 m and 3 m × 3 m, respectively. Tree height was measured primarily with a total station, while diameter at breast height (DBH) was measured using a tape. For shrubs, both plant height and stem diameter were measured with a steel tape.

2.2.3 Biomass method

Plants synthesize carbohydrates from water and carbon dioxide through photosynthesis. A portion of these carbohydrates is consumed by plant respiration, while the remainder is allocated to the formation of stems, branches, leaves, roots, and other tissues. The carbon sequestration of herbaceous plants can be calculated using the biomass method (Equation 4) (Figure 2), with the formula as follows:

$$T_{\text{carbon sequestration}} = T_{\text{plant}} \times \beta \times \frac{44}{12} \quad (4)$$

where, $T_{\text{carbon sequestration}}$ denotes the carbon sequestration per unit area; T_{plant} represents the plant biomass; β is the carbon content ratio. The carbon content ratio (β) recommended by the IPCC is 0.5 (Parry, 2007).

The procedure for estimating plant biomass consisted of the following steps: (i) A 1 m × 1 m quadrat was established, with three parallel quadrats delineated for the same plant type; (ii) All plants within each quadrat, including roots, were collected and transported to the laboratory; (iii) Samples were dried in an oven at 65 °C until a constant weight was achieved, and the dry weight-representing plant biomass was measured.

2.3 Cluster analysis

Cluster analysis was performed on the carbon sequestration capacity per unit land area of 31 tree species and 18 shrub species using the average linkage method (UPGMA). The analysis was implemented in R software. Squared Euclidean distance was employed as the similarity measure, and species were classified into high, medium, and low grades based on their carbon sequestration efficiency. By calculating the average distance between clusters to construct a dendrogram, this method objectively reflects the similarity in carbon sequestration capacity among species, providing a statistical basis for identifying high-

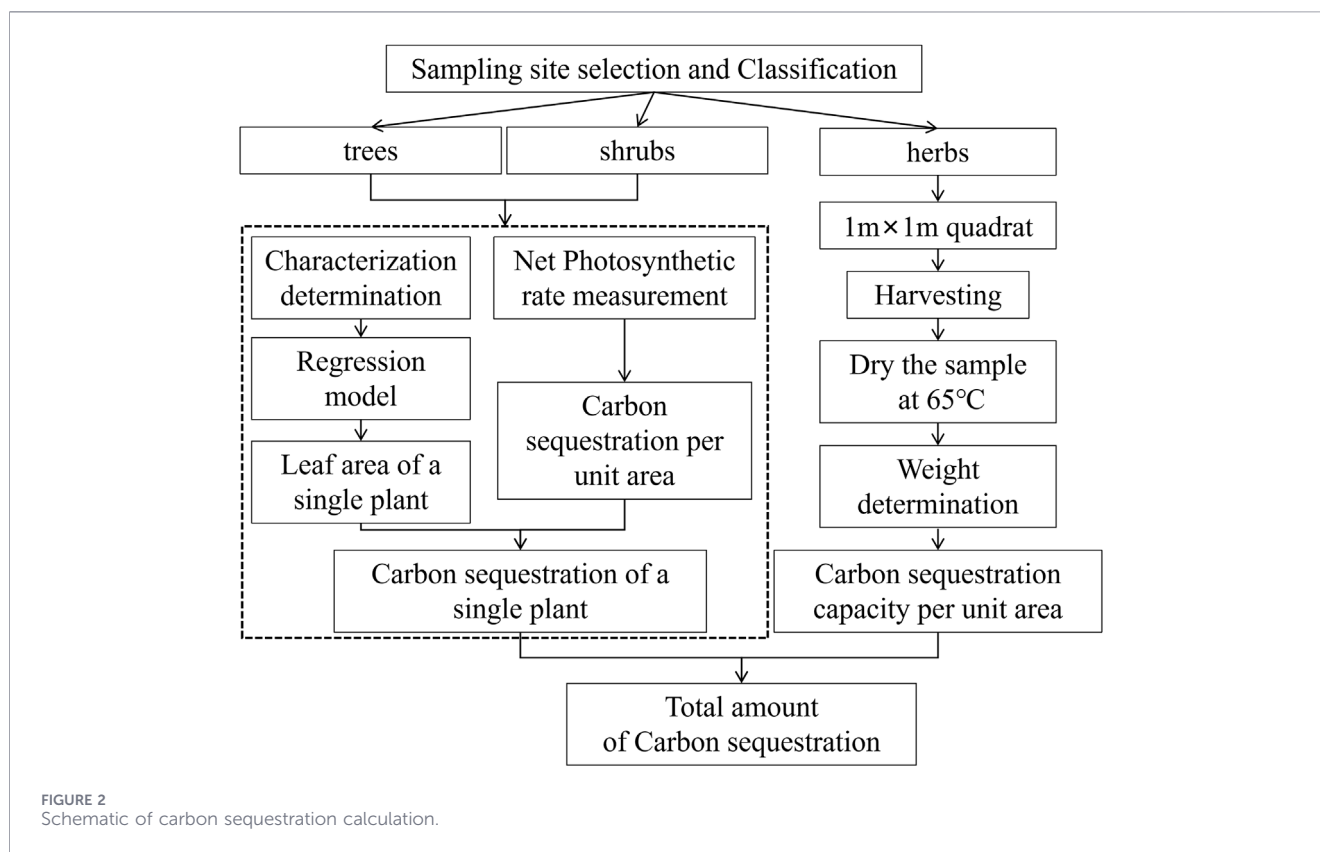


TABLE 1 Regression model for calculating the leaf area index.

No.	Species	Regression equation		
		Chen et al. (1998)	Shen (2007)	Shen (2007)
1	<i>Sabina chinensis</i> cv. <i>Pyramidalis</i>		$L = 0.583W + 0.877$	$L = 8.927D + 0.708$
2	<i>Magnolia grandiflora</i>		$L = 0.815W + 1.115$	$L = 20.094D + 1.148$
3	<i>Cedrus deodara</i>		$L = 0.163W + 0.996$	$L = 3.708D + 0.937$
4	<i>Sophora japonica</i>		$L = 0.118W + 1.013$	$L = 3.725D + 0.951$
5	<i>Metasequoia glyptostroboides</i>		$L = 0.289W + 3.698$	$L = 5.096D + 3.907$
6	<i>K. bipinnata</i>	$S = 4.88W + 44.89H - 94.26$		
7	<i>Ginkgo biloba</i>	$S = 8.8W + 18.93H - 123.02$	$L = 0.630W + 0.970$	$L = 10.138D + 1.900$
8	<i>Amygdalus persica</i> L.var. <i>persica</i> f. <i>atropurpurea</i> Schneid	$S = 1.61H + 3.17D - 7.17$	$L = 0.117W + 1.426$	$L = 4.415D + 1.327$
9	<i>Salix babylonica</i>	$S = 7.43W + 21.97H - 72.38$		
10	<i>Magnolia liliiflora</i>		$L = 0.815W + 1.115$	$L = 20.094D + 1.148$

potential carbon sequestration species and optimizing roadside vegetation configuration.

2.4 Data sources

The data on the number of tree and shrub plants, as well as the planted area of herbaceous combinations, were provided by both the design unit of the G4 Expressway Hubei Section and the expressway management company.

3 Results and discussion

3.1 Annual carbon sequestration of different plants

The calculated annual total carbon sequestration for the 31 tree species along the G4 Expressway (Dawu-Caidian section) is 18,909,856 kg. The 18 shrub species contribute an annual total of 12,309,285 kg, while the four herbaceous combinations sequester

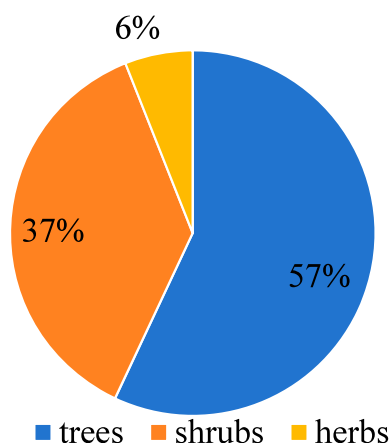


FIGURE 3
Contribution of different vegetation species in total carbon sequestration.

1,945,542 kg per year. Consequently, the combined annual carbon sequestration by these three vegetation types along the 158-km section totals 33,165 tons, averaging approximately 210 tons per kilometer. Among the vegetation types along the expressway, trees account for the largest proportion (57%, Figure 3) of the total carbon sequestration, followed by shrubs (37%), and herbaceous plants (6%). This highlights the dominant role of trees in determining the carbon sequestration capacity of roadside vegetation (Chang et al., 2025).

Statistical analysis of data in Tables 2–4 reveals a non-linear relationship between planting quantity and annual carbon sequestration. Among the trees, *Sabina chinensis* cv. *Pyramidalis* has the highest planting count (47,889 individuals), but its annual carbon sequestration (1,775,915 kg) is not the highest. In contrast, *K. bipinnata*, with a considerably smaller population (9,781 individuals), achieves a remarkably high annual sequestration of 7,110,569 kg, constituting 37.60% of the total tree sequestration and demonstrating exceptionally high carbon sequestration efficiency per individual. Similarly, *Triadica sebifera*, with only 7,691 individuals, contributes 2,291,024 kg annually, further underscoring the decisive role of species-specific photosynthetic and morphological traits in carbon sink potential (Jin et al., 2023). Among shrubs, *Nerium oleander*, despite having a smaller population (12,416 individuals) compared to *Cercis chinensis* (18,719) and *Photinia × fraseri* (18,188), yields the highest annual carbon sequestration (2,840,292 kg). This reflects its combined advantages in carbon fixation efficiency per unit leaf area and canopy structure.

The total annual carbon sequestration along the studied G4 section (~33,165 t, ~210 tons·km⁻¹·a⁻¹) is lower than that reported for the Shanghai-Nanjing G42 expressway (~97,000 t, ~354 t km⁻¹·a⁻¹) (Fu et al., 2019). This discrepancy arises from multiple factors: (i) species-specific efficiency—the top-performing tree on G42 (*Koeleruteria paniculata*, 70.82 kg m⁻²·a⁻¹) substantially exceeds the top species on G4 (*Pterocarya stenoptera*, ~46.8 kg m⁻²·a⁻¹); (ii) vegetation configuration—trees contribute 74.87% of total carbon sequestration on G42 versus only 57% on G4; (iii) climatic conditions—the G42 corridor experiences a more humid climate with higher annual precipitation, which potentially supports greater plant growth and

biomass accumulation; and (iv) vegetation maturity—the G42 vegetation had been growing for over a decade, whereas some G4 sections are younger or recently renovated. These comparisons highlight that maximizing roadside carbon sinks requires selecting high-efficiency species, optimizing tree-shrub-herb configuration, allowing sufficient maturation time, and accounting for regional climatic conditions.

Detailed photosynthetic parameters at the species level, leaf area index, and estimation methods can be found in Supplementary Tables S1, S2.

3.2 Carbon sequestration efficiency of different species

Regarding carbon sequestration efficiency per unit land area, among the tree species, *Pterocarya stenoptera* (128.10 g m⁻²·d⁻¹) and *Liquidambar formosana* (126.41 g m⁻²·d⁻¹) exhibited the most outstanding performance (Figure 4). Their values were substantially higher than those of other trees, indicating their strong carbon sink potential per unit ground area. Although *Ginkgo biloba* demonstrated very high annual carbon sequestration per individual, its sequestration per unit land area was only 87.37 g m⁻²·d⁻¹. This suggests that its relatively lower ground-area efficiency may be attributed to a larger crown spread or lower planting density. It is also noteworthy that *Sabina chinensis* cv. *Pyramidalis*, which had the highest planting quantity, showed a sequestration rate of only 20.698 g m⁻²·d⁻¹ per unit land area, coupled with a low rate per unit leaf area. This further confirms that its carbon sequestration efficiency is not prominent, and its primary role is likely landscaping and protective functions in the expressway central divider (Jian and Hongyi, 2017; Zhang, 2019).

Among the shrubs, *Photinia × fraseri* achieved the highest carbon sequestration per unit land area (73.11 g m⁻²·d⁻¹), significantly exceeding other shrub species (Figure 4). Its sequestration per unit leaf area (22.07 g m⁻²·d⁻¹) was also the highest, reflecting its dual advantages in leaf photosynthetic efficiency and canopy structure. In comparison, although *Nerium oleander* had the highest total annual carbon sequestration per individual, its sequestration per unit land area was only 49.90 g m⁻²·d⁻¹, indicating that its efficiency per unit area is lower than that of *Photinia × fraseri*. *Hypericum monogynum* showed a relatively high carbon sequestration per unit leaf area (14.57 g m⁻²·d⁻¹), but its value per unit land area was moderate. This may be constrained by its canopy thickness and leaf area index.

The cluster analysis results (Figures 5, 6) categorized trees and shrubs into high, medium, and low carbon sequestration classes based on their carbon sequestration capacity per unit land area.

Among the trees, species such as *Pterocarya stenoptera*, *Liquidambar formosana*, *Ginkgo biloba*, *Triadica sebifera*, and *K. bipinnata* were classified into the high carbon sequestration group. Their common characteristics include a high leaf area index, an expansive canopy structure, and a relatively high photosynthetic rate. These species demonstrate significant carbon sink advantages per unit land area and are particularly suitable as dominant species for roadside greening. The medium carbon sequestration group, which includes species like *Cinnamomum camphora* and *Cunninghamia lanceolata*,

TABLE 2 Carbon sequestration of individual tree species.

No.	Species	Crown height (m)	Diameter at breast high (cm)	Crown diameter (m)	Carbon sequestration of a single plant (g CO ₂ /d)	Numbers	Annual carbon sequestration capacity (kg CO ₂)
1	<i>Sabina chinensis</i> cv. <i>Pyramidalis</i>	1.5 ± 0.85	12 ± 3.13	2.50 ± 0.04	101.60 ± 15.64	47889	1775916 ± 273426
2	<i>Cinnamomum camphora</i>	2.42 ± 0.39	8.77 ± 3.52	2.03 ± 0.24	79.48 ± 2.63	15082	437532 ± 14452
3	<i>Elaeocarpus decipiens</i>	4 ± 1.36	40 ± 5.02	5.00 ± 0.12	364.84 ± 7.41	13757	1831973 ± 37185
4	<i>Magnolia grandiflora</i>	8.5 ± 3.22	50 ± 14.52	8.50 ± 1.29	3163.73 ± 64.74	76	87762 ± 1796
5	<i>Osmanthus fragrans</i>	2.1 ± 0.27	12.53 ± 1.81	2.33 ± 0.16	115.42 ± 3.48	431	18157 ± 547
6	<i>Cedrus deodara</i>	6.5 ± 0.12	35 ± 8.86	7.50 ± 0.56	399.60 ± 19.22	41	5980 ± 288
7	<i>Eriobotrya japonica</i>	4.5 ± 0.09	35 ± 15.38	6.00 ± 0.39	1748.37 ± 6.20	210	134013 ± 476
8	<i>Myrica rubra</i> (Lour.) S. et Zucc	3 ± 0.97	27.5 ± 12.75	4.50 ± 0.37	327.52 ± 6.62	231	27615 ± 558
9	<i>Citrus maxima</i>	4.4 ± 1.07	12.07 ± 3.54	2.64 ± 0.47	251.09 ± 11.70	264	24195 ± 1127
10	<i>Michelia maudiae</i>	5 ± 2.49	25 ± 10.63	5.50 ± 0.61	880.18 ± 7.18	25	8032 ± 66
11	<i>Triadica sebifera</i>	5.13 ± 0.67	14.93 ± 7.11	4.37 ± 0.29	816.12 ± 5.61	7691	2291024 ± 15740
12	<i>Sophora japonica</i>	2.91 ± 0.46	10 ± 0.87	3.25 ± 0.29	250.22 ± 0.41	6710	612826 ± 1007
13	<i>Metasequoia glyptostroboides</i>	3.5 ± 1.42	7.5 ± 2.19	3.50 ± 1.08	384.93 ± 9.22	7036	988554 ± 23691
14	<i>K. bipinnata</i>	4.5 ± 0.08	7.7 ± 2.93	6.50 ± 0.83	1991.72 ± 12.75	9781	7110570 ± 45501
15	<i>Ginkgo biloba</i>	8.5 ± 3.42	67 ± 19.84	10.50 ± 3.35	7565.14 ± 277.75	379	1046524 ± 38422
16	<i>Amygdalus persica</i> <i>L. var. persica</i> f. <i>atropurpurea</i> Schneid	4 ± 0.22	40 ± 4.35	4.00 ± 0.45	389.69 ± 16.77	425	60451 ± 2602
17	<i>Salix babylonica</i>	6.5 ± 0.33	18.1 ± 2.52	7.00 ± 0.64	4240.34 ± 74.42	116	179536 ± 3151
18	<i>Taxodium ascendens</i>	4 ± 1.35	45 ± 18.64	4.50 ± 0.54	603.28 ± 4.77	816	179681 ± 1419
19	<i>Sinocalmus affinis</i>	4.5 ± 0.52	6 ± 1.96	3.50 ± 0.12	352.15 ± 1.59	238	30591 ± 138
20	<i>Bambusa multiplex</i> (Lour.) Raeusch. ex Schult	2.25 ± 0.31	3.5 ± 1.19	2.00 ± 0.24	71.34 ± 3.20	457	11900 ± 533
21	<i>Taxodium distichum</i> (L.) Rich	4 ± 0.91	65 ± 0.74	3.50 ± 0.68	413.70 ± 0.75	247	37297 ± 68
22	<i>Pterocarya stenoptera</i>	9.5 ± 1.61	75 ± 19.84	10.00 ± 1.42	10060.87 ± 2342.14	77	282761 ± 65826
23	<i>Sapindus saponaria</i>	6.5 ± 0.66	60 ± 27.98	8.00 ± 0.54	4485.97 ± 80.40	206	337300 ± 6045
24	<i>Albizia julibrissin</i>	6.5 ± 2.74	35 ± 2.87	7.00 ± 0.31	1543.79 ± 4.91	214	120585 ± 384
25	<i>Prunus yedoensis</i> Matsum	3 ± 0.81	20 ± 3.56	4.50 ± 0.22	537.53 ± 1.06	741	145383 ± 286
26	<i>Magnolia liliiflora</i>	3 ± 0.09	17.5 ± 3.59	3.00 ± 0.45	285.85 ± 3.40	325	33909 ± 404
27	<i>P. halliana</i>	3 ± 0.59	17.5 ± 3.85	3.00 ± 0.33	257.67 ± 8.50	268	25205 ± 832
28	<i>Acer buergerianum</i>	4.5 ± 0.63	35 ± 0.81	6.50 ± 1.1	1948.36 ± 76.65	142	100983 ± 3973
29	<i>Liquidambar formosana</i>	8 ± 1.33	75 ± 32.31	10.50 ± 0.63	10945.52 ± 272.44	165	659194 ± 16408

(Continued)

TABLE 2 Continued

No.	Species	Crown height (m)	Diameter at breast high (cm)	Crown diameter (m)	Carbon sequestration of a single plant (g CO ₂ /d)	Numbers	Annual carbon sequestration capacity (kg CO ₂)
30	<i>Liriodendron chinense</i> × <i>tulipifera</i>	5 ± 0.04	60 ± 9.19	6.50 ± 0.2	2064.93 ± 49.97	381	287159 ± 6949
31	<i>A. palmatum</i> 'Atropurpureum'	3.81 ± 1.90	9.5 ± 2.47	3.53 ± 0.53	270.02 ± 2.67	175	17248 ± 170

TABLE 3 Carbon sequestration of individual shrub species.

No.	Species	Crown diameter (m)	Leaf layer thickness (m)	Carbon sequestration of a single plant (g CO ₂ /d)	Numbers	Annual carbon sequestration capacity (kg CO ₂)
1	<i>Photinia</i> × <i>fraseri</i>	1.52 ± 0.26	1.73 ± 0.26	132.10 ± 8.53	18188	876960 ± 56648
2	<i>Loropetalum chinense</i> var. <i>rubrum</i>	0.90 ± 0.15	0.65 ± 0.15	22.62 ± 4.20	9408	77659 ± 14426
3	<i>Ligustrum japonicum</i> 'Howardii'	1.25 ± 0.22	0.80 ± 0.04	34.67 ± 5.91	6138	77685 ± 13231
4	<i>Pyracantha fortuneana</i>	1.50 ± 0.59	0.90 ± 0.13	60.17 ± 17.31	15782	346617 ± 99708
5	<i>Nerium oleander</i>	4.00 ± 1.16	1.50 ± 0.33	626.74 ± 136.07	12416	2840292 ± 616668
6	<i>Ilex cornuta</i> Lindl. et Paxt	2.25 ± 0.03	1.10 ± 0.19	89.39 ± 7.05	4721	154041 ± 12142
7	<i>Osmanthus fragrans</i> 'Semperflorens'	3.00 ± 0.89	1.50 ± 0.28	235.03 ± 19.11	10643	913012 ± 113102
8	<i>Pittosporum tobira</i>	2.00 ± 0.79	1.15 ± 0.29	52.05 ± 13.77	672	12766 ± 3378
9	<i>Gardenia jasminoides</i>	1.15 ± 0.04	1.10 ± 0.06	40.76 ± 2.35	1693	25188 ± 1453
10	<i>Ligustrum C</i>	1.40 ± 0.26	0.80 ± 0.13	21.26 ± 1.69	1665	12919 ± 1025
11	<i>Rhododendron simsii</i>	1.00 ± 0.32	0.50 ± 0.09	25.04 ± 1.61	2095	19147 ± 1234
12	<i>Hypericum monogynum</i>	0.90 ± 0.33	0.70 ± 0.19	29.41 ± 8.35	172	1846 ± 524
13	<i>Prunus cerasifera</i> cv. <i>pissardii</i>	3.75 ± 0.33	—	458.90 ± 83.53	16192	2712112 ± 493681
14	<i>Lagerstroemia indica</i>	1.52 ± 0.51	1.21 ± 0.17	65.30 ± 3.78	15650	373027 ± 21581
15	<i>Cercis chinensis</i>	2.10 ± 0.47	1.50 ± 0.25	317.29 ± 76.51	18719	2167849 ± 522754
16	<i>H. syriacus</i>	1.70 ± 0.41	2.01 ± 0.29	31.91 ± 9.37	14690	171075 ± 50261
17	<i>Hibiscus mutabilis</i>	2.50 ± 0.50	1.85 ± 0.38	248.35 ± 73.28	16591	1503913 ± 443787
18	<i>Prunus</i> × <i>blireana</i> cv. <i>Meiren</i>	3.50 ± 1.17	1.70 ± 0.44	362.85 ± 92.65	175	23177 ± 5918

possesses a certain level of carbon sequestration capacity, albeit with lower efficiency compared to the former group. They can serve as auxiliary or background planting. The low carbon sequestration group, comprising species such as *Sabina*

chinensis cv. *Pyramidalis* and *Bambusa multiplex*, may offer advantages in morphology or stress tolerance, but their carbon sink function is limited. Thus, they are not preferred species for carbon sequestration-oriented planning.

TABLE 4 Annual carbon sequestration of herbs.

No.	Species	Biomass in unit area (kg·m ⁻²)	Carbon sequestration in unit land area (kg CO ₂ ·m ⁻² ·a ⁻¹)	Area (m ²)	Annual carbon sequestration capacity (kg CO ₂)
1	<i>Coreopsis grandiflora</i> Hogg.+ <i>Cynodon dactylon</i> + <i>Cosmos bipinnatus</i> Cav	0.732	1.340	1284609	1721752
2	<i>Parthenocissus tricuspidata</i>	0.516	0.945	82648	78085
3	<i>Trifolium repens</i> L	0.395	0.723	183099	132426
4	<i>Campsis grandiflora</i> (Thunb.) Schum	0.451	0.826	16080	13279

The shrub clustering results (Figure 6) indicate that *Photinia × fraseri*, *Nerium oleander*, and *Hibiscus mutabilis* belong to the high carbon sequestration class, exhibiting both high carbon sequestration efficiency per unit leaf area and high canopy density. *Photinia × fraseri*, in particular, combines high per-unit-leaf-area and high per-unit-land-area sequestration capacities, making it a suitable primary carbon sink species for the shrub layer. Shrubs in the medium and low carbon sequestration classes, such as *Buxus sinica* var. *parvifolia* and *Rhododendron simsii*, contribute less significantly to carbon sequestration and primarily fulfill roles in landscape ornamentation or ground cover.

3.3 Roadside vegetation planting strategy

To enhance the carbon sink function of expressway roadside areas, the following vegetation and afforestation strategies are recommended:

1. For trees, priority should be given to high-carbon-sequestration species such as *Pterocarya stenoptera*, *Liquidambar formosana*, *Triadica sebifera*, *Ginkgo biloba*, and *K. bipinnata*, with their planting proportion appropriately increased. For shrubs, key species such as *Photinia × fraseri*, *Nerium oleander*, and *Hibiscus mutabilis* should be promoted, given their high carbon sequestration efficiency per unit area and strong adaptability.
2. Research indicates that species richness and diversity of seedlings, herbaceous plants, and shrubs are positively correlated with biomass and soil carbon storage (Helal, 2015). A three-dimensional “tree-shrub-herb” configuration is recommended: the upper layer should consist of tall, broad-crowned trees to provide shade and form a major carbon storage layer; the middle layer should include dense shrubs to enhance carbon sequestration per unit land area; and the ground layer should be covered with mixed herbaceous species (e.g., *Coreopsis* spp. + *Cynodon dactylon*) to achieve rapid coverage and auxiliary carbon sequestration.
3. In key carbon-enhancement zones (e.g., slopes, central dividers), high-efficiency carbon-sequestration species should be concentrated. In areas where landscape or protective functions are primary, medium or low-efficiency species may be retained appropriately. By rationally regulating planting density and canopy

structure, the photosynthetically active area and carbon sequestration efficiency per unit land area can be further improved.

Regarding the recommendation of non-native species, *N. oleander* and *Photinia × fraseri* were identified as high-potential carbon-sequestering shrubs due to their superior carbon sequestration efficiency per unit land area, substantially exceeding that of most native species. However, the potential ecological risks associated with introducing non-native species, such as biological invasion or disruption to local ecosystems, are fully acknowledged. To mitigate these risks, the following precautionary measures are recommended: (1) prioritize the use of known sterile cultivars to minimize dispersal; (2) conduct rigorous ecological risk assessments prior to planting and align deployment with regional ecological safety planning; (3) establish long-term monitoring programs to evaluate impacts on native species and ecosystems. These high-efficiency non-native species may be appropriately deployed in priority areas for carbon sink enhancement (e.g., slopes along high-emission expressway sections), while ecologically sensitive areas should prioritize high-carbon native species (e.g., *T. sebifera*, *L. formosana*).

Regarding the practicality of the three-layer planting strategy, the proposed “tree-shrub-herb” multi-layer configuration theoretically maximizes carbon sequestration per unit land area, but its implementation must account for real-world constraints. Water availability is a critical limiting factor, particularly in arid or semi-arid regions; therefore, adopting water-saving irrigation techniques (e.g., drip irrigation, mulching) during establishment and prioritizing drought-tolerant species (e.g., *N. oleander*, *T. sebifera*) are recommended. Long-term maintenance requirements (e.g., pruning, pest control, replanting) may also affect sustainability, suggesting a tiered maintenance approach: intensive management in high-priority carbon sink zones, while general greening areas rely primarily on natural succession with minimal interventions. Additionally, planting density should be optimized based on site-specific conditions to avoid growth limitations from excessive competition.

3.4 Uncertainty analysis

The error sensitivity analysis demonstrates a strictly proportional relationship between input error in diurnal net photosynthetic rate and the resulting error in calculated carbon

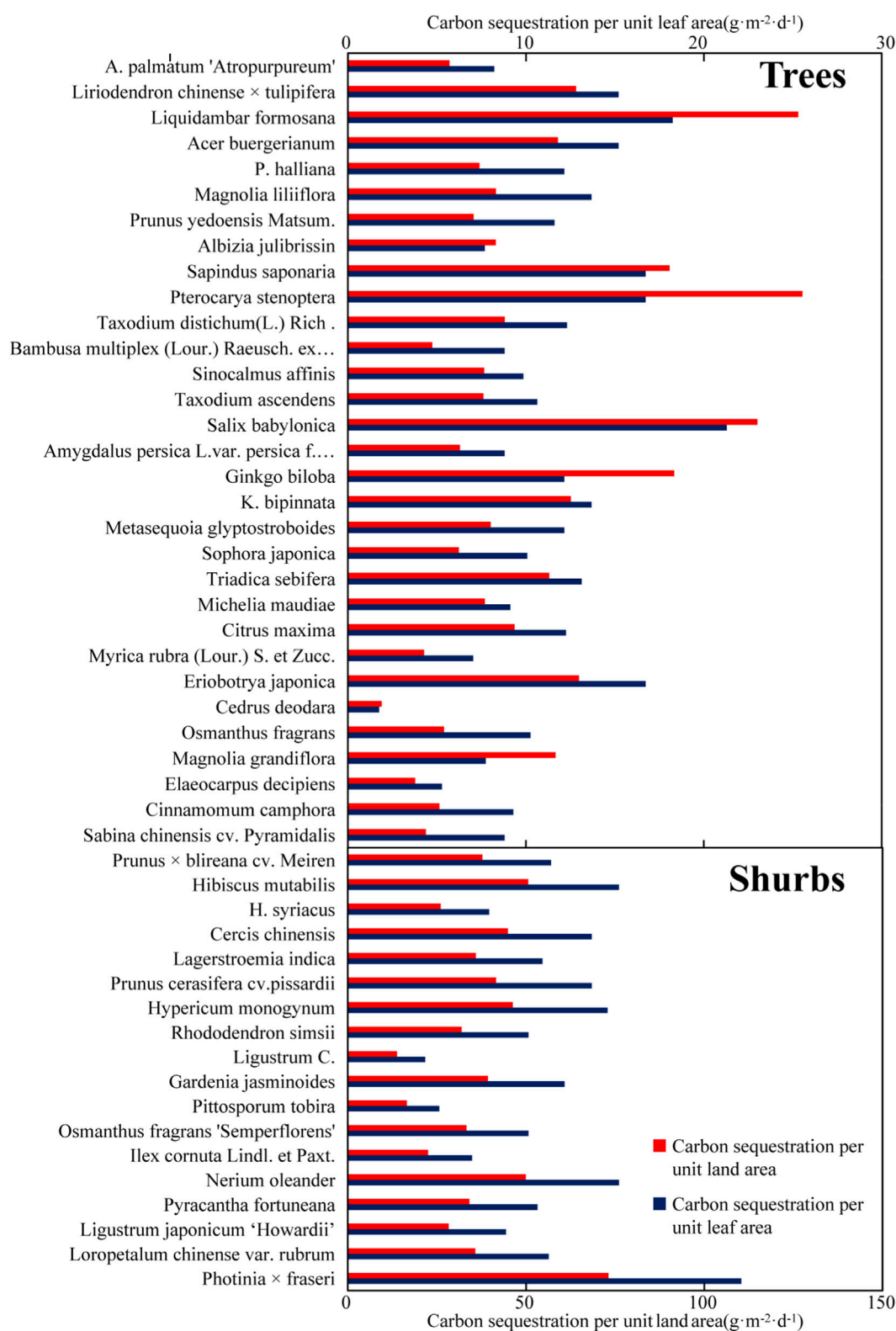
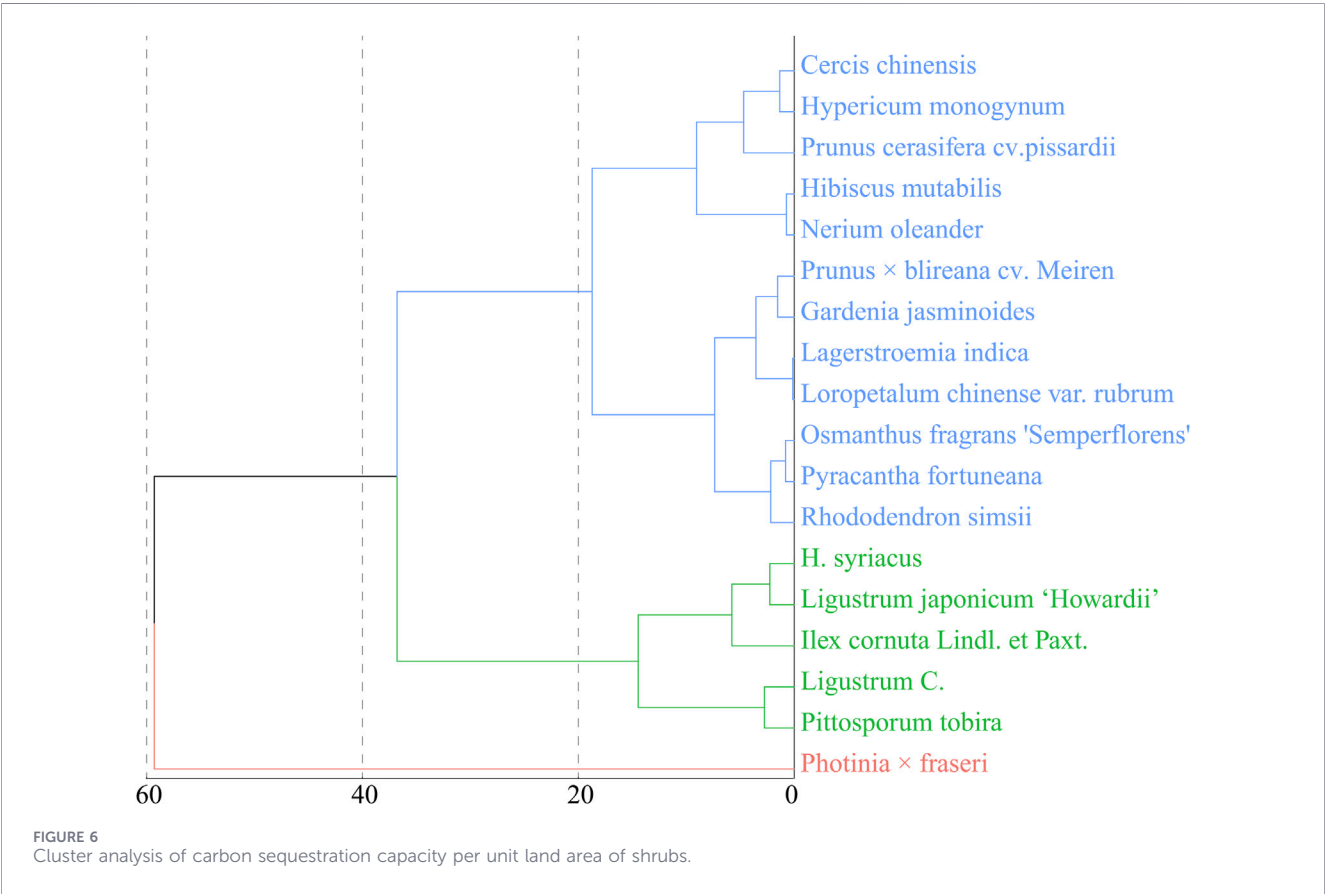
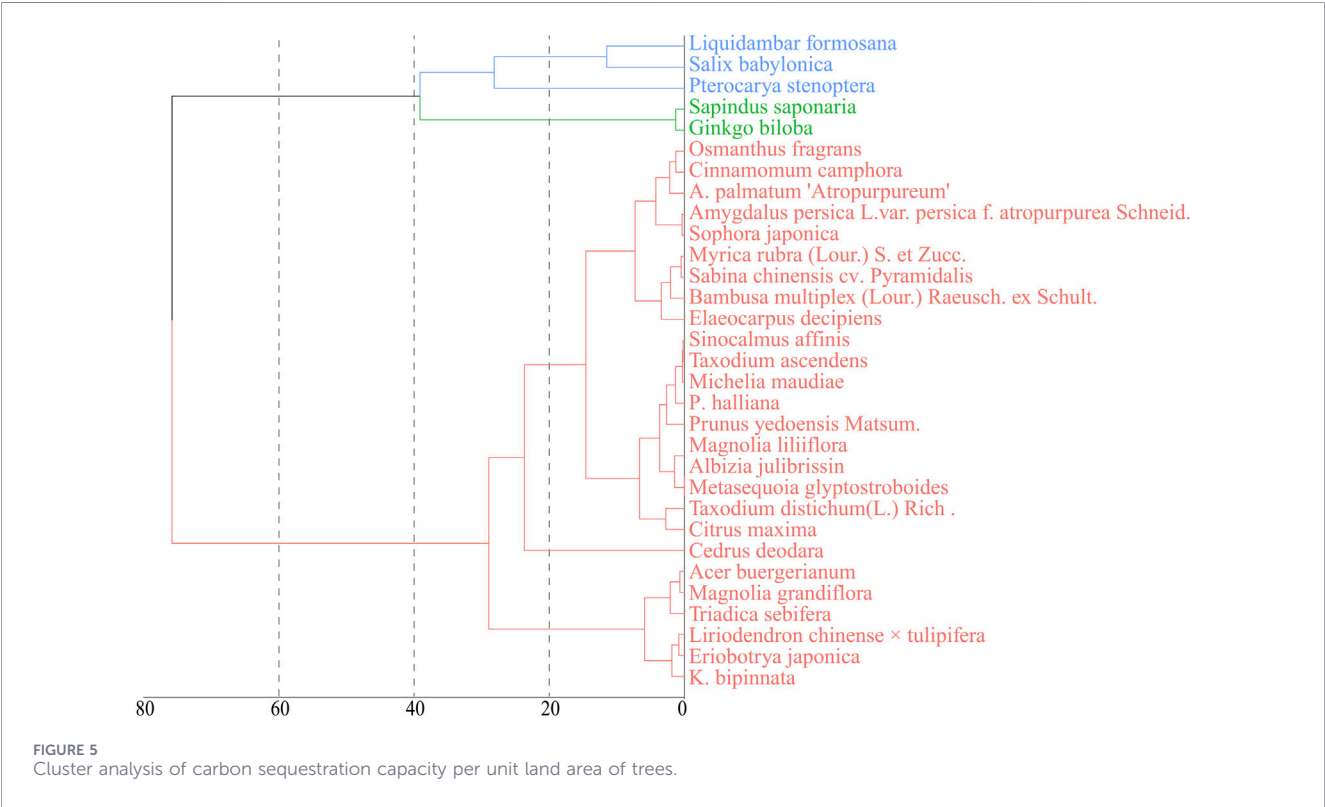


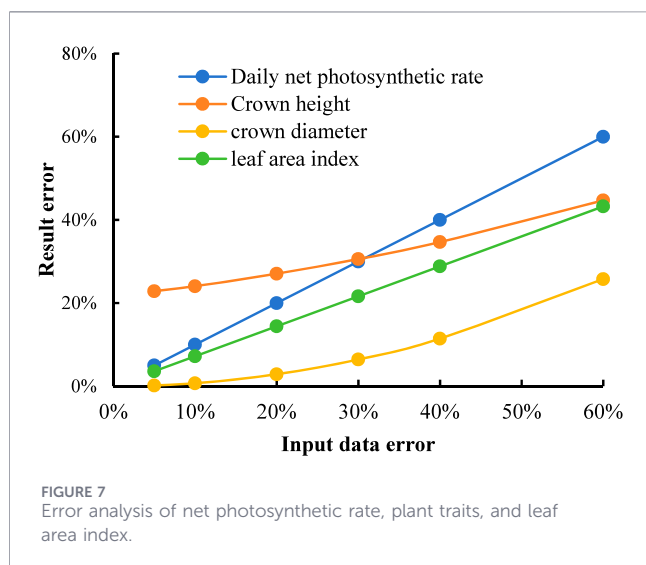
FIGURE 4

The carbon sequestration rates per unit land/leaf area for different types of trees and shrubs.

sequestration (Figure 7). This highlights the critical importance of precise photosynthetic measurement, which was ensured in this study through multi-season, multi-timepoint field measurements using the Li-6400 portable photosynthesis system.

Crown height exhibited the highest sensitivity among all parameters: a 5% input error propagated to a 22.85% output error, while a 60% error resulted in 44.69% inaccuracy. Although total station instruments ensured measurement precision, some





deviation may persist for species with complex crown structures, warranting focused attention in future studies.

Crown diameter showed the lowest sensitivity, with a 60% input error yielding only 25.78% output error, indicating high tolerance for measurement inaccuracies in this parameter.

Leaf area index displayed intermediate sensitivity (60% input error → 43.25% output error). As a critical link between leaf-level photosynthetic efficiency and land-area-based carbon sequestration, LAI estimation in this study relied on regression equations and field sampling.

The plant species and quantities in this study were derived from on-site construction plans. Accordingly, uncertainty in the results primarily arises from measurement system error and leaf area estimation error. Measurement procedures followed technical specifications, yet inherent uncertainties from manual operation and instrumentation were considered by assuming a 5% systematic error, leading to a corresponding 5% error in the final results.

Leaf area was not directly measured due to research constraints but was estimated using regression models linking morphological traits to leaf area index. This constitutes the main source of uncertainty. To minimize bias, we selected species-specific regression models for 10 target species from previous studies in China; for the remaining species, comprehensive tree or shrub regression models were applied. Validation against the 10 species-specific models showed that the comprehensive models had an average estimation error of 39.82%, ultimately contributing an error of less than 30% to the final carbon sequestration estimates.

The robustness of the average linkage clustering analysis primarily depends on data variability and the significance of inter-class distances. In this study, variability mainly stems from interspecific physiological differences and potential measurement errors. Error sensitivity analysis identified crown height and leaf area index as influential parameters, but the carbon sequestration values differ markedly across clusters—high-sequestration species such as *Pterocarya stanoptera* far exceed low-sequestration species like *Sabina chinensis*. These substantial inter-class distances ensure that minor estimation errors do not alter the primary classification. Additionally, the UPGMA method effectively

smooths random noise, reducing outlier impact. Although species near cluster boundaries may exhibit some sensitivity, the overall classification remains stable, providing a reliable basis for identifying high-potential carbon-sequestering species. Future studies with larger sample sizes could further enhance classification stability.

3.5 Research Prospects

Based on the year-round seasonal measurements already conducted in this study, future research should be further expanded in the following directions: Temporally, multi-year continuous monitoring is needed to assess the interannual variability and long-term dynamics of vegetation carbon sinks; spatially, the research scope should be extended to expressways in different climatic zones to reveal regional differences in carbon sequestration capacity and their driving mechanisms; methodologically, eddy covariance techniques can be introduced to validate existing calculations, while remote sensing and UAV technologies should be integrated to improve the spatial coverage and accuracy of carbon sink assessments; for species selection, a multi-indicator comprehensive evaluation framework incorporating ecological adaptability, stress resistance, and biological invasion risk should be developed; at the application level, long-term field experiments are needed to verify the actual carbon sink performance of different configuration models and their responses to real-world constraints such as water availability and maintenance; ultimately, interdisciplinary integration should promote the functional transformation of expressways from carbon sources to carbon sinks, providing scientific support for achieving carbon neutrality in the transportation sector.

4 Conclusion

This study evaluated the carbon sequestration capacity of roadside vegetation along a 158 km section of the G4 Expressway in central China. The total annual carbon sequestration of 31 tree species, 18 shrub species, and four herbaceous combinations reached approximately 33,165 tons, with trees contributing 57%, shrubs 37%, and herbs 6%. While shrubs exhibited higher carbon sequestration per unit leaf area, trees with high leaf area indices—such as *P. stanoptera*, *Liquidambar formosana*, and *Triadica sebifera*—demonstrated superior performance per unit land area. Among shrubs, *Photinia × fraseri*, *Nerium oleander*, and *Hibiscus mutabilis* ranked as the most efficient species.

Cluster analysis classified trees and shrubs into high, medium, and low carbon sequestration categories based on unit land area capacity, providing a robust basis for species selection. The results underscore that photosynthetic efficiency and canopy structure are more decisive for carbon sink performance than planting quantity alone.

To enhance roadside carbon sinks, we recommend prioritizing native species with high photosynthetic efficiency and leaf area index, and implementing a multi-layered “tree-shrub-herb” configuration tailored to site-specific conditions. Despite year-round measurements, this study is limited by its single-site scope and reliance on regression-based leaf area estimation. Future research should extend across climatic zones, employ eddy covariance and remote sensing technologies, and conduct long-term field experiments to validate configuration performance under real-world constraints.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Author contributions

CC: Data curation, Investigation, Software, Writing – original draft, Validation, Visualization. ZA: Formal Analysis, Funding acquisition, Investigation, Writing – original draft, Conceptualization, Methodology, Supervision. XY: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Validation, Writing – review and editing. WJ: Conceptualization, Funding acquisition, Methodology, Project administration, Validation, Visualization, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was funded by the “Key Technologies Research and Application Demonstration for Carbon Neutrality in Highway Infrastructure (KJFZ-2022-001)”.

Conflict of interest

Authors CC and ZA were employed by China Communications Construction Hemei Eco-environmental Construction Co. Ltd.

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Author XY was employed by Wuhan Zhongneng Huayuan design consulting Co., Ltd.

The remaining author(s) declared that this work 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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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2026.1771385/full#supplementary-material>

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