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Carbon Fixation and Oxygen Release Capacity of Typical Riparian Plants in Wuhan City and Its Influencing Factors

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Abstract: In order to explore the carbon fixation and oxygen release capabilities of riparian plants in Wuhan, the photosynthetic rate (Pn) and morphological indicators of 13 typical riparian plants in the middle section of the Xunsi River in Wuhan were measured by portable photosynthesis apparatus. The daily carbon fixation and oxygen release of each plant at different scales were calculated, and the carbon fixation and oxygen release capacity and its influencing factors were analyzed. The results show that: (1) according to the biological characteristics, the daily carbon fixation and oxygen release capacity per unit leaf area was higher in herbaceous than in trees; the daily carbon fixation and oxygen release capacity per plant, per projected area, and per land area were higher in trees than in herbaceous. (2) The plant with the strongest ability of daily carbon fixation and oxygen release per unit leaf area was *Ruellia brittoniana*, and the weakest was *Triadica sebifera*; the plant with the strongest ability of daily carbon fixation and oxygen release of a single plant was *Metasequoia glyptostroboides*, and the weakest was *Lolium perenne*; the plant with the strongest ability of daily carbon fixation and oxygen release per land area was *Metasequoia glyptostroboides*, and the weakest was *Alternanthera sessilis*. (3) The carbon fixation and oxygen release ability of 13 plant species was analyzed by cluster analysis based on per unit leaf area, per plant, and per land area; ten species of herbaceous plant could be divided into three grades and three species of trees into two grades. This study provides a theoretical reference for the selection and application of riparian zone vegetation in Wuhan, and provides a scientific basis for the evaluation of riparian zone ecological benefits.

Keywords: carbon fixation and oxygen release; riparian plants; morphological indicators; cluster analysis; impact factors

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1. Introduction

Excessive CO_2 emissions are the primary cause of the global greenhouse effect, resulting in various issues such as climate change and global warming, which significantly impact human daily life [1]. To achieve the climate goal of limiting global warming to 1.5 °C as outlined in the Paris Agreement, the IPCC has proposed in its Sixth Assessment Report that global carbon emissions should be promptly reduced and carbon neutrality should be achieved. Therefore, in the context of promoting the "dual-carbon" goal, a green and low-carbon approach is necessary to attain carbon neutrality [2,3]. Plants are recognized as vital green ecological resources, playing a crucial role in carbon sequestration and oxygen release, which are essential for ecosystems. Plants are indispensable and hold significant ecological value in addressing global climate change and realizing carbon neutrality [4]. Rivers, as integral components of urban ecosystems, play a pivotal role in the virtuous cycle of urban ecosystems [5].

Scholars at home and abroad have conducted extensive research on plant carbon sequestration and oxygen release. Shi [6] investigated the oxygen sequestration capacity of dominant landscape plants in Wuhan and found that shrubs had a higher Pn and oxygen sequestration per unit area compared to trees. William L. Bauerle [7] studied the photosynthetic capacity of leaves from 23 tree species and observed that the photosynthetic capacity reached its peak after the summer solstice. Matthias Forke [8] highlighted the significance of climate–vegetation–carbon cycle feedback in high-latitude regions and demonstrated that photosynthetic carbon sequestration has contributed to warming in recent decades. They also found that photosynthetic carbon uptake responded more strongly to warming than carbon release. Liu [9] studied the carbon sequestration and oxygen release capacity of Lonicera japonica, a common garden plant, and investigated the effects of cadmium stress on the growth, photosynthesis, carbon sequestration, and oxygen release characteristics of Lonicera japonica. Jin [10] studied the carbon sequestration potential of 32 typical tree species in Zhengzhou City. However, the carbon sequestration patterns of many unique greening species in riparian zones remain unclear, as most studies have focused on the carbon sequestration and oxygen sequestration capacities of terrestrial plants in urban gardens. Several studies have examined the carbon sequestration and oxygen release capacity of individual plant species in the riparian zone, such as *Phragmites australis* and *Cortaderia selloana* [11,12], as well as plants in the reservoir floodplain [13]. However, these studies did not thoroughly investigate the carbon sequestration and oxygen release patterns of typical plants in the urban riparian zone. The carbon sequestration and oxygen release capacities of different plants can vary significantly due to their distinct biological characteristics. Therefore, it is crucial to understand the oxygen sequestration and release capacity of typical plants in the urban riparian zone in order to accurately estimate the carbon sink capacity and ecological benefits of the riverbank zone. Investigating the carbon sequestration and oxygen release capacity of typical plants in urban riparian zones is of utmost importance for estimating the carbon sink capacity and ecological benefits of riparian zones.

Wuhan, known as “the city of a hundred lakes”, is characterized by its extensive network of rivers and lakes, which cover almost 25% of the city’s area. These water bodies play a crucial role in maintaining the regional water balance and regulating the local climate. The riparian zone, where water and land interact, is of particular importance. It not only helps reduce pollution inputs and prevent soil erosion but also serves as a carbon neutralizer through the vegetation present in this zone. Our study focuses on the middle section of the Xunsi River in Wuhan, which serves as the riparian zone for Wuhan. We selected 13 representative riparian zone plants in this area and measured their leaf traits and net Pn. We compared the daily net carbon sequestration and oxygen release per unit of leaf area, per plant, and per unit of land area. Additionally, we analyzed the main factors influencing the daily net carbon sequestration and oxygen release of these plants. Our aim is to understand the carbon sequestration and oxygen release characteristics of plants in typical riparian zones in the Wuhan region. This research provides valuable insights into vegetation selection and ecological restoration in the riparian zones of Wuhan. The purpose of this study is to investigate the carbon sequestration and oxygen release characteristics of plants in typical riparian zones in Wuhan. The findings will provide a reference basis for the selection and application of vegetation in the ecological restoration project of Wuhan riparian zone, as well as theoretical support for evaluating the ecological benefits of riparian zone vegetation.

2. Materials and Methods

2.1. Regional Overview

The test site is situated in the riparian zone of the middle section of the Xunsi River in Wuhan City, with geographical coordinates of 114°31′ E and 30°49′ N Figure 1. The area experiences a humid subtropical monsoon climate, with an average temperature ranging from 13 to 22 °C over multiple years. The average precipitation is approximately 1205 mm, and it exhibits noticeable annual and seasonal variations. The river is located in Hongshan District, Wuhan City, Hubei Province, with a total length of about 13.7 km and an average river width of about 50 m, passing through several campuses and residential areas along the way, with the surrounding land types mainly consisting of educational land, residential land, a small amount of agricultural land, and urban green space in the unincorporated area, with a regional species richness of 14.352 and a vegetation cover of 46.2%. The design area of this experiment is about 650 m in length, with a height difference of 3.5 m at the highest point and 3 m at the lowest point, and a total area of about 76,300 m^2.

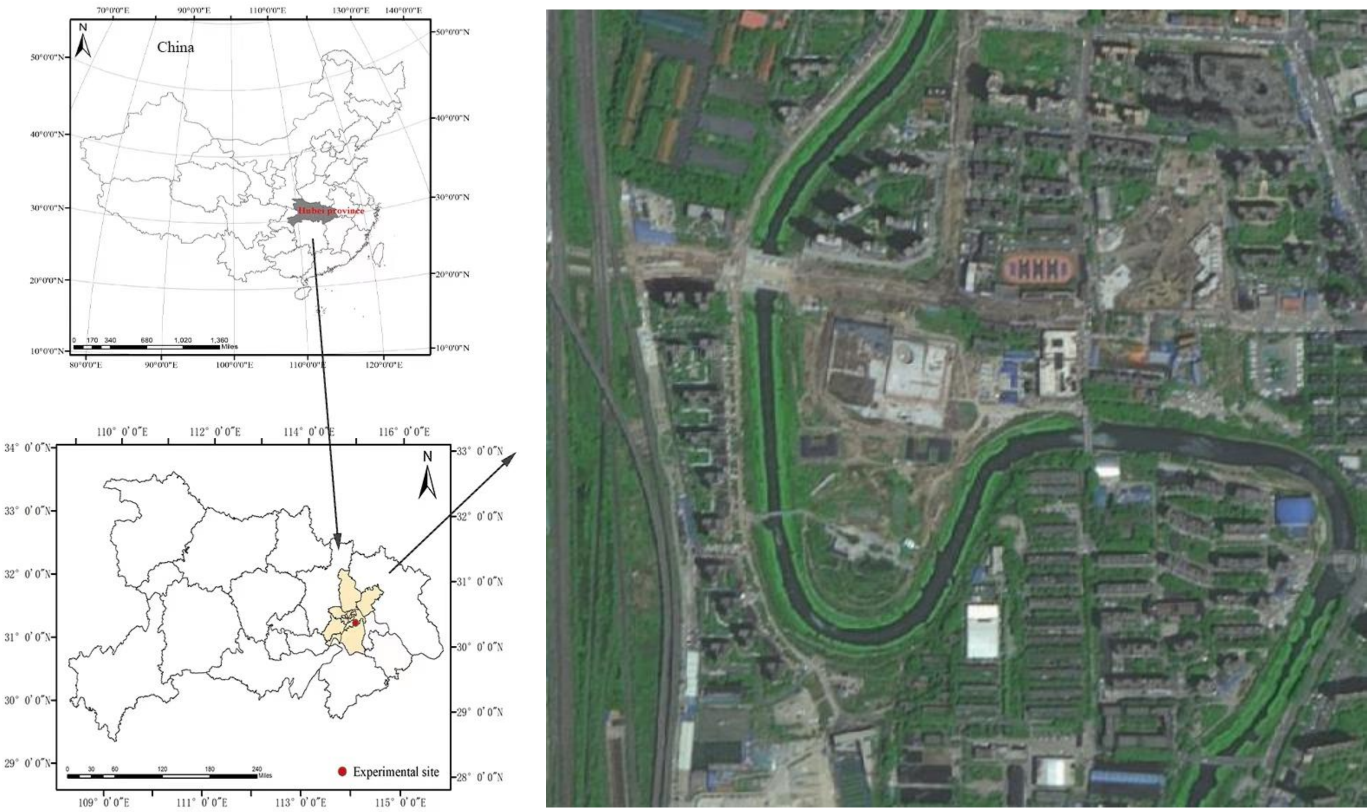


Figure 1. Regional overview map of the XunSi River in Wuhan.

2.2. Test Materials

In late July 2022, during the peak growth period for plants in summer, field research was conducted to identify suitable plants in the river's riparian zone. The selection of plant materials was based on suitability and sustainability. Suitability includes the plant's ability to grow under Wuhan's specific climate, soil, and water resources to ensure that the selected plants can grow healthily in Wuhan's riparian zone. Meanwhile, sustainability takes into account the environmental impacts of the way the plant material is obtained, including how it is planted, how it is collected, and how it is recycled. A total of 13 dominant plant species from 10 families were screened out. Based on their biological characteristics, 10 species were herbaceous plants: *Cynodon dactylon*, *Lolium perenne*, *Ruellia brittoniana*, *Lythrum salicaria*, *Cortaderia selloana*, *Hydrocotyle vulgaris*, *Alternanthera sessilis*, *Pontederia cordata*, *Typha orientalis*, and *Phragmites australis*. The remaining 3 species were arborvitae: *Metasequoia glyptostroboides*, *Salix babylonica*, and *Triadica sebifera*. Table 1 provides the basic information for these 13 species. For each plant species, 5 sample plots were selected using a specific sampling method. The sample plots for herbaceous plants measured 1 m × 1 m, while those for arborvitae measured 20 m × 20 m. All plants were measured in the field research for their height, planting density, diameter at breast height, and crown width. Table 1 also presents the basic information of the sample plots.

Table 1. Growth indicators and planting density of 13 selected plants.

Name of Plant	Type of Plant	Average Plant Height (m)	Average Plant Diameter at Breast Height (cm)	Average Plant Crown Area (m^2)	Planting Density (Plant/hm^2)
Cynodon dactylon	perennial	0.07 ± 0.01	——	——	1.90×10^7
Lolium perenne	perennial	0.11 ± 0.03	——	——	1.80×10^7
Ruellia brittoniana	perennial	1.50 ± 0.17	——	——	3.50×10^5
Lythrum salicaria	perennial	1.03 ± 0.21	——	——	5.00×10^5
Cortaderia selloana	perennial	1.51 ± 0.10	——	——	8.00×10^4
Hydrocotyle vulgaris	perennial	0.20 ± 0.02	——	——	2.50×10^5
Alternanthera sessilis	perennial	0.67 ± 0.05	——	——	2.20×10^5
Pontederia cordata	perennial	1.03 ± 0.21	——	——	2.00×10^4
Typha orientalis	perennial	2.04 ± 0.22	——	——	1.00×10^5
Phragmites australis	perennial	2.85 ± 0.27	——	——	5.50×10^5
Metasequoia glyptostroboides	deciduous tree	10.80 ± 2.18	38.03 ± 7.0	20.70 ± 5.19	1.65×10^3
Salix babylonica	deciduous tree	5.69 ± 0.51	24.70 ± 4.03	22.08 ± 3.05	1.00×10^3
Triadica sebifera	deciduous tree	10.41 ± 0.66	54.90 ± 11.9	24.85 ± 5.33	6.00×10^2

Note: Planting density is calculated with reference to GB T 15776-2016 [14] Technical Regulations for Afforestation and DB42/T 1977–2023 [15] Technical Regulations for Afforestation and Greening on Both Sides of the Yangtze River.

2.3. Test Methods

2.3.1. Determination of Plant Leaf Traits

In the study to compare leaf area, five representative sample plants were first selected from each plant. The number of leaves of each plant was recorded using the standard branching method, which is a commonly used method to estimate the leaf area of a plant. Subsequently, six healthy and intact leaves were removed from each plant and placed in ice packs to maintain freshness. These leaves were then brought back to the laboratory for subsequent processing. In the laboratory, the leaves were image-processed using Fiji software v2.3.0, through which the area of the leaves could be accurately calculated. Based on the number of leaves recorded and the results of image processing, the total leaf area of the entire investigated plant could be calculated. The specific leaf area (SLA) of the plants was calculated using the following formula:

$$SLA = \frac{S}{W_{dry}},$$

where SLA is the specific leaf area of the plant (cm^2/g), S is the projected area of the leaf (cm^2), and W_{dry} is the dry weight of the leaf (g).

The leaf area index (LAI) of trees is calculated using the formula method (Table 2). Before calculating LAI, the plant biomass model established in previous studies was utilized to calculate the whole-plant leaf dry weight of the tree. This biomass model includes parameters such as tree height, diameter at breast height, and crown projected area of the tree, which can be combined to derive the leaf dry weight of the tree. Alternatively, samples of arborvitae leaves may be collected for weighing and area measurement to derive leaf area and leaf total directly. LAI was then calculated using a specific formula.

$$LAI = \frac{W \cdot SLA}{C},$$

where LAI is the leaf area index of the plant, W is the dry weight of the whole leaf of the plant (kg), and C is the canopy area of the plant (m^2).

Table 2. Tree biomass model.

Name of Plant	Plant Organ	Mathematical Equation	Source
Metasequoia glyptostroboides	leave	W = 3.54 − 0.014DH + 0.00009223(DH)^2	[16]
Salix babylonica	leave	W = 0.025(D^{2}H)$^{1.1778}$	[17]
Triadica sebifera	leave	W = 3.035D^2	[18]

2.3.2. Measurement of Carbon Sequestration and Oxygen Release

Determination of net photosynthesis rate: the net Pn of plants was determined during the summer when plant growth and metabolism are most active and photosynthetic carbon sequestration and oxygen release are at their peak. Measurements were conducted using a 3051D portable photosynthesis analyzer under clear, cloudless, and windless weather conditions. The measurements were taken at 2-h intervals from 8:00 to 18:00 in natural light. For each plant, three healthy, disease-free, and pest-free standard sample plants were selected. Measurements were taken on the sunny side of each plant, using leaves of the same size and health. The measurements were repeated three times, and the leaves were spread out in the leaf compartment to avoid overlap. Five instantaneous values of net Pn were recorded for each measurement and averaged.

Calculation of oxygen sequestration capacity: the daily oxygen sequestration capacity of plants can be determined by analyzing the daily change of net photosynthesis rate, based on the principle of plant photosynthesis. This can be achieved by calculating the area under the curve formed by the daily change of net photosynthesis rate over time. Furthermore, the daily assimilation capacity per unit of leaf area can be directly calculated using the integration method. The formula for daily assimilation is used in this calculation:

$$P = \sum_{i=1}^{j} (((P_{i+1} + P_i)/2)(t_{i+1} - t_i) \times 3600/1000),$$

where P is the daily assimilation per unit leaf area on the measurement day (mmol·m^{-2}·d^{-1}), P_i is the instantaneous Pn at the initial measurement point (μmol·m^{-2}·s^{-1}), P_{i+1} is the instantaneous Pn at the next measurement point (μmol·m^{-2}·s^{-1}), t_i is the instantaneous time at the initial measurement point (h), t_{i+1} is the instantaneous time at the next measurement point (h), j is the number of tests, and 3600 is the number of seconds in an hour.

The dark respiration consumption of plants at night was calculated as 20% of the daytime assimilation, and the total assimilation on the measurement day was converted to the fixed CO_2 on the measurement day by the following formula:

$$W_{CO_2} = P \times (1 - 0.2) \times 44/1000,$$

where W_{CO2} is the mass of CO_2 fixed by leaves per unit area (g·m^{-2}·d^{-1}) and 44 is the relative molecular mass of CO_2.

The formula for calculating the daily oxygen release of plants is:

$$W_{O_2} = P \times (1 - 0.2) \times 32/1000,$$

where W_{O2} is the mass of O_2 released per unit area of leaf (g·m^{-2}·d^{-1}) and 32 is the relative molecular mass of O_2.

The formula for calculating the daily carbon sequestration and oxygen release of a single plant is as follows:

$$S_{co_2/o_2} = W_{co_2/o_2} \times S,$$

where S_{CO2} is the mass of CO_2 fixed by single plant leaves (g/d), S_{O2} is the mass of O_2 released by single plant leaves (g/d), and S is the total leaf area of single plant.

The formula for calculating the daily carbon sequestration and oxygen release per unit land area is:

$$Q_{co_2/o_2} = S_{co_2/o_2} \times planting\ density,$$

where Q_{CO2} is the mass of CO_2 fixed per unit land area (kg·hm^2·d^{-1}) and Q_{O2} is the mass of O_2 released per unit land area (kg·hm^2·d^{-1}).

2.4. Data Analysis

The carbon sequestration and oxygen release capacity per unit of leaf area, as well as per unit of land area, of 13 experimental plants were statistically analyzed using Excel 2013 and SPSS 25.0 software. Cluster analysis was conducted using the Word Method of sum of squares of departures to generate cluster analysis plots for the different plants. The software used for generating the cluster analysis plots was Origin 2017.

3. Results and Analysis

3.1. Plant Leaf Traits

In this study, we conducted measurements and comparisons of leaf traits (Table 3) for 13 typical riparian zone plants in the middle section of the Xunsi River in Wuhan City. According to Table 3, *Metasequoia glyptostroboides* had the highest leaf dry weight per plant at 13.35 kg, followed by weeping willow, *Salix babylonica*, *Triadica sebifera*, *Cortaderia selloana*, *Phragmites australis*, *Typha orientalis*, *Pontederia cordata*, *Ruellia brittoniana*, *Hydrocotyle vulgaris*, *Alternanthera sessilis*, *Lythrum salicaria*, *Cynodon dactylon*, and *Lolium perenne* in descending order. The lowest leaf dry weight was found in *Lolium perenne*, with a weight of 0.000013 kg. LAI of *Metasequoia glyptostroboides* were slightly higher than those of *Salix babylonica*, and significantly higher than those of the other plants, with values of 11.33 and 10.46, respectively. *Triadica sebifera*, *Phragmites australis*, *Cortaderia selloana*, *Pontederia cordata*, *Lolium perenne*, *Typha orientalis*, *Hydrocotyle vulgaris*, *Alternanthera sessilis*, *Lolium perenne*, *Lythrum salicaria*, and *Cynodon dactylon* followed with LAI ranging from 11.33 to 0.84. When analyzing the classification of different biological characteristics, it was observed that the leaf area index of trees (9.47) was significantly higher than that of herbaceous plants (2.36). The specific leaf area of mushroom grass was the highest at 27.2, followed by *Lolium perenne*, *Lythrum salicaria*, *Alternanthera sessilis*, *Salix babylonica*, *Cynodon dactylon*, *Triadica sebifera*, *Metasequoia glyptostroboides*, *Pontederia cordata*, *Phragmites australis*, *Ruellia brittoniana*, *Typha orientalis*, and *Cortaderia selloana*. Cattail had the lowest specific leaf area at 3.32. When considering the classification of different biological characteristics, the specific leaf area of trees (18.89) was higher than that of herbaceous plants (15.29).

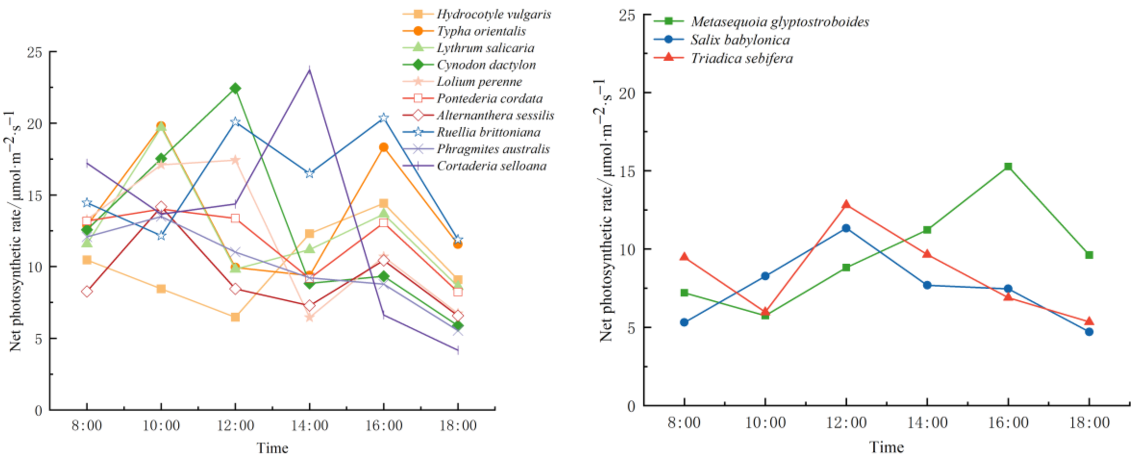
Table 3. Plant leaf characteristics.

Name of Plant	Leaf Area per Plant (m^2)	Leaf Dry Weight per Plant (kg)	Leaf Area Index	Specific Leaf Area(m^2/kg)
Cynodon dactylon	$2.51 \times 10^{-3} \pm 3.20 \times 10^{-4}$ c	$1.21 \times 10^{-4} \pm 2.81 \times 10^{-5}$ d	0.84 ± 0.04 ef	20.34 ± 2.31 bc
Lolium perenne	$6.01 \times 10^{-4} \pm 3.40 \times 10^{-5}$ c	$1.33 \times 10^{-5} \pm 7.20 \times 10^{-6}$ d	1.33 ± 0.20 ef	23.23 ± 2.51 ab
Ruellia brittoniana	$7.58 \times 10^{-2} \pm 5.12 \times 10^{-3}$ c	$8.91 \times 10^{-3} \pm 4.32 \times 10^{-4}$ d	2.48 ± 0.07 de	8.51 ± 0.45 e
Lythrum salicaria	$8.30 \times 10^{-3} \pm 6.70 \times 10^{-4}$ c	$3.82 \times 10^{-4} \pm 6.11 \times 10^{-5}$ d	0.88 ± 0.01 f	21.94 ± 1.79 bc
Cortaderia selloana	$9.03 \times 10^{-1} \pm 1.40 \times 10^{-2}$ c	$2.72 \times 10^{-1} \pm 3.31 \times 10^{-2}$ d	3.61 ± 0.30 c	3.32 ± 0.09 f
Hydrocotyle vulgaris	$1.37 \times 10^{-1} \pm 1.40 \times 10^{-2}$ c	$5.04 \times 10^{-3} \pm 4.22 \times 10^{-4}$ d	1.67 ± 0.07 ef	27.20 ± 1.81 a
Alternanthera sessilis	$1.41 \times 10^{-2} \pm 2.8 \times 10^{-3}$ c	$6.65 \times 10^{-4} \pm 3.63 \times 10^{-5}$ d	1.54 ± 0.03 ef	21.29 ± 0.93 bc
Pontederia cordata	$2.40 \times 10^{-1} \pm 3.14 \times 10^{-2}$ c	$1.61 \times 10^{-2} \pm 2.88 \times 10^{-3}$ d	3.39 ± 0.15 cd	14.88 ± 0.75 d
Typha orientalis	$1.19 \times 10^{-1} \pm 1.38 \times 10^{-2}$ c	$3.25 \times 10^{-2} \pm 6.10 \times 10^{-3}$ d	2.36 ± 0.13 de	3.66 ± 0.31 f
Phragmites australis	$3.28 \times 10^{-1} \pm 4.53 \times 10^{-2}$ c	$3.81 \times 10^{-2} \pm 4.12 \times 10^{-3}$ d	5.56 ± 0.31 b	8.61 ± 0.77 e
Metasequoia glyptostroboides	234.63 ± 12.57 a	13.35 ± 1.21 a	11.33 ± 0.43 a	17.58 ± 1.20 cd
Salix babylonica	230.94 ± 13.55 a	10.89 ± 1.32 b	10.46 ± 0.45 a	21.21 ± 2.03 bc
Triadica sebifera	164.52 ± 10.20 b	9.20 ± 0.84 b	6.62 ± 0.32 b	17.88 ± 2.14 cd

Note: Tables with the same labeled letters indicate non-significant differences, and those with completely different labeled letters indicate significant differences (the same below).

3.2. Daily Variation of Photosynthetic Rate

The daily variation curves and peak values of net Pn differed among the 13 plants examined in this study (Figure 2). The net Pn peaks occurred at different times, resulting in two categories of curves: single-peak and double-peak. The single-peak curves of *Hydrocotyle vulgaris*, *Cynodon dactylon*, *Phragmites australis*, *Cortaderia selloana*, *Metasequoia glyptostroboides*, *Salix babylonica*, and *Triadica sebifera* displayed an increasing trend up to the peak, followed by a decrease. The peaks of *Cynodon dactylon*, *Phragmites australis*, *Salix babylonica*, and *Triadica sebifera* were observed between 10:00 and 16:00, while the peaks of *Hydrocotyle vulgaris*, *Cortaderia selloana*, and *Metasequoia glyptostroboides* occurred between 14:00 and 18:00. The plants with bimodal net Pn curves were *Typha orientalis*, *Lythrum salicaria*, *Lolium perenne*, *Pontederia cordata*, *Alternanthera sessilis*, and *Ruellia brittoniana*. These plants showed an initial increase in NPP followed by a gradual decrease, then a decrease to a trough, and a subsequent increase, followed by another decrease after the second peak. *Typha orientalis*, *Lythrum salicaria*, *Pontederia cordata*, and *Alternanthera sessilis* exhibited their first and second peaks between 10:00–12:00 and 16:00–18:00, respectively. *Lolium perenne* and *Ruellia brittoniana*, on the other hand, had their first peaks between 12:00 and 14:00. *Typha orientalis*, *Lolium perenne*, *Pontederia cordata*, *Alternanthera sessilis*, and *Ruellia brittoniana* rue reached their troughs between 14:00 and 16:00, while *Lythrum salicaria* reached its trough between 12:00 and 14:00.



(**a**) (**b**)

Figure 2. Daily variation of plant net photosynthetic rate ((**a**): herbaceous daily net photosynthetic rate (**b**): tree daily net photosynthetic rate).

3.3. Analysis of Plant Carbon Sequestration and Oxygen Release Capacity

3.3.1. Analysis of Plant Carbon Sequestration and Oxygen Release Capacity per Unit Leaf Area

According to Figure 3, *Ruellia brittoniana* had the highest daily carbon sequestration and oxygen release per unit leaf area among the 10 herbaceous plants, with values of 10.42 $g{\cdot}m^{-2}{\cdot}d^{-1}$ and 7.58 $g{\cdot}m^{-2}{\cdot}d^{-1}$, respectively. On the other hand, *Alternanthera sessilis* had the lowest values, with 6.05 $g{\cdot}m^{-2}{\cdot}d^{-1}$ for carbon sequestration and 4.40 $g{\cdot}m^{-2}{\cdot}d^{-1}$ for oxygen release. Among the three species of arboriculture, *Metasequoia glyptostroboides* had the highest daily carbon sequestration and oxygen release per unit leaf area, with values of 6.27 $g{\cdot}m^{-2}{\cdot}d^{-1}$ and 4.56 $g{\cdot}m^{-2}{\cdot}d^{-1}$, respectively. *Triadica sebifera* had the lowest values, with 5.42 $g{\cdot}m^{-2}{\cdot}d^{-1}$ for carbon sequestration and 3.94 $g{\cdot}m^{-2}{\cdot}d^{-1}$ for oxygen release. In terms of plant morphology, most of the herbaceous plants (except for *Alternanthera sessilis*) had significantly higher daily carbon sequestration and oxygen release per unit leaf area compared to the tree plants. Additionally, the average daily carbon sequestration and oxygen release per unit leaf area of the herbaceous plants were significantly higher than those of the trees. The average daily carbon sequestration and oxygen release per unit leaf area of the herbaceous plants was 1.37 times higher than that of the trees, and *Ruellia brittoniana* accounted for 13.13% of the daily carbon sequestration and oxygen release among the 10 herb species. This phenomenon may be due to the fact that herbaceous plants have a high chlorophyll content, which favors photosynthetic capacity, and that chlorophyll is mainly distributed between the cytoplasm of the leaf cytoplasm and the thin walls of the chloroplasts, thus enhancing the efficiency of light absorption and transmission. In contrast, tree plants have lower chlorophyll content, which is mainly distributed in the epidermal cells of leaves to minimize the loss of excess light energy.

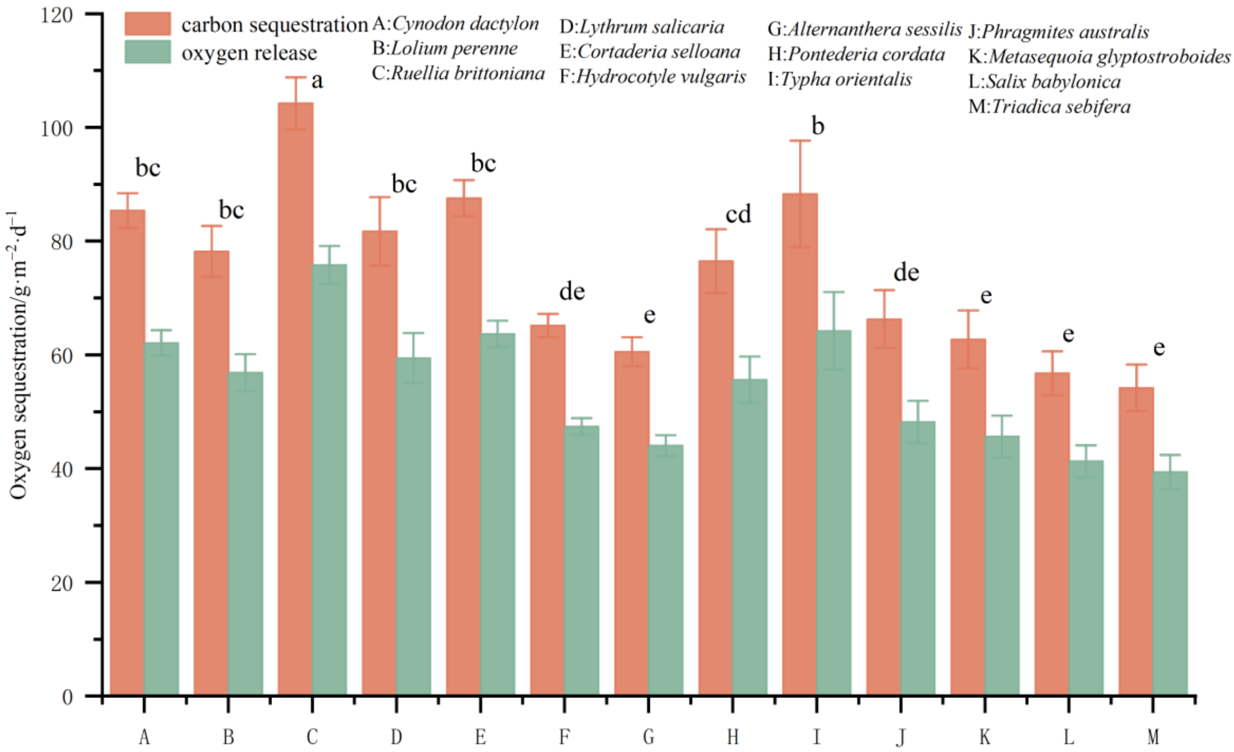


Figure 3. Daily carbon sequestration and oxygen release per unit leaf area of plants.

3.3.2. Analysis of the Capacity of a Single Plant to Sequester Carbon and Release Oxygen

According to Figure 4, there were significant differences in the daily carbon sequestration and oxygen release by a single plant among the 10 herbaceous plants. The *Cortaderia selloana* had the highest daily carbon sequestration of 7.9 $g \cdot d^{-1}$ and oxygen release of 5.75 $g \cdot d^{-1}$, while *Lolium perenne* had the lowest with 0.0047 $g \cdot d^{-1}$ and 0.003 $g \cdot d^{-1}$, respectively. Among the three tree plants, *Metasequoia glyptostroboides* had the highest daily carbon sequestration by single plant of 1471.32 $g \cdot d^{-1}$ and oxygen release by single plant of 1070.05 $g \cdot d^{-1}$, whereas *Triadica sebifera* had the lowest with 891.25 $g \cdot d^{-1}$ and 648.18 $g \cdot d^{-1}$, respectively. From a plant morphology and classification perspective, trees exhibited significantly higher daily carbon sequestration and oxygen release by single plants compared to herbaceous plants. On average, trees had 826 times higher daily carbon sequestration and oxygen release by single plants than herbaceous plants. Additionally, among the three tree species, *Metasequoia glyptostroboides* accounted for 40% of the daily carbon and oxygen sequestration by a single plant.

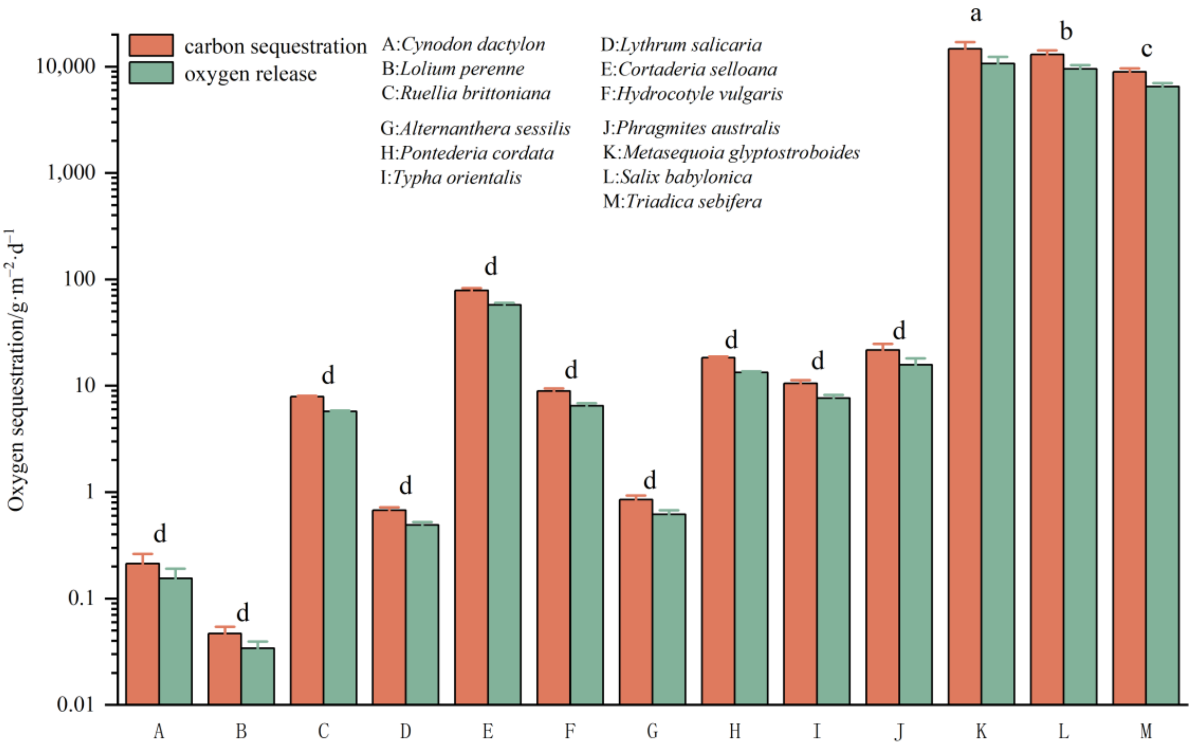


Figure 4. Daily carbon sequestration and oxygen release of single plants.

3.3.3. Analysis of Plants' Capacity to Sequester Carbon and Release Oxygen per Unit Land Area

The analysis of carbon sequestration and oxygen release capacity per unit land area compares the carbon sequestration and oxygen release capacity of different plants under the same spatial resource conditions. This analysis helps in selecting the appropriate planting plan to maximize the carbon sequestration and oxygen generation per unit land area. Figure 5 shows the carbon sequestration and oxygen release per unit land area of 10 herbaceous plants as follows: *Phragmites australis* > *Cortaderia selloana* > *Cynodon dactylon* > *Ruellia brittoniana* > *Hydrocotyle vulgaris* > *Typha orientalis* > *Lolium perenne* > *Pontederia cordata* > *Lythrum salicaria* > *Alternanthera sessilis*. Among these, *Phragmites australis* had the highest daily carbon sequestration and oxygen release per unit land area, with values of 119.46 $kg \cdot hm^{-2} \cdot d^{-1}$ and 86.88 $kg \cdot hm^{-2} \cdot d^{-1}$, respectively. On the other hand, *Alternanthera sessilis* had the lowest values, with only 1.87 $kg \cdot hm^{-2} \cdot d^{-1}$ and 1.36 $kg \cdot hm^{-2} \cdot d^{-1}$. Among the three tree species, carbon sequestration and oxygen release per unit land area were highest for *Metasequoia glyptostroboides*, followed by *Salix babylonica* and *Triadica sebifera*. *Metasequoia glyptostroboides* had the largest daily carbon sequestration and oxygen release per unit land area, with values of 242.75 $kg \cdot hm^{-2} \cdot d^{-1}$ and 176.55 $kg \cdot hm^{-2} \cdot d^{-1}$, respectively. *Triadica sebifera* had the lowest values, with 53.47 $kg \cdot hm^{-2} \cdot d^{-1}$ and 38.89 $kg \cdot hm^{-2} \cdot d^{-1}$, respectively. From the perspective of plant morphology, trees exhibit significantly higher daily carbon sequestration and oxygen release per unit of land area compared to herbs. On average, trees have 4.73 times higher daily carbon sequestration and oxygen release per unit of land area than herbs. Moreover, the average daily carbon and oxygen sequestration per unit land area of trees is 4.73 times higher than that of herbs. Among the three species, *Metasequoia glyptostroboides* accounts for 56.82% of the daily carbon and oxygen sequestration per unit land area.

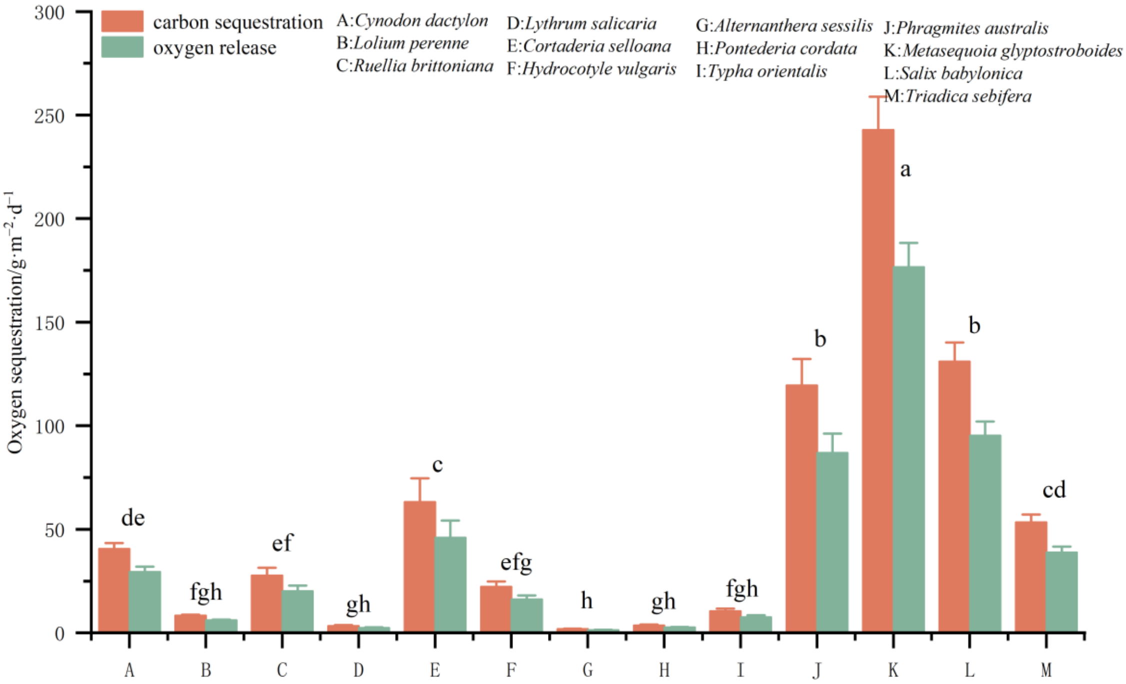


Figure 5. Daily carbon sequestration and oxygen release per unit land area of plants.

3.4. Correlation Analysis

3.4.1. Correlation Analysis between Instantaneous Net Photosynthetic Rate of Plants and Environmental Factors

The daily changes in the net Pn of 13 plant species were analyzed in relation to various environmental factors. Table 4 presents the results, indicating that the instantaneous net Pn of the plants exhibited highly significant positive correlations ($p < 0.01$) with photosynthetically active radiation (PAR), leaf temperature (Ti), and relative humidity (RH). Additionally, significant positive correlations ($p < 0.05$) were observed with atmospheric temperature (Ta), while no significant correlations ($p < 0.05$) were found with atmospheric CO_2 concentration (Ci) and intercellular CO_2 concentration (Ca).

Table 4. Correlation analysis between instantaneous net photosynthetic rate of plants and environmental factors.

	Pn	Ta	PAR	Ti	Ci	RH	Ca
Pn	1						
Ta	0.228 *	1					
PAR	0.360 **	0.737 **	1				
Ti	0.355 **	0.779 **	0.648 **	1			
Ci	0.105	−0.267 *	−0.136	−0.061	1		
RH	0.323 **	0.218	0.804 **	0.273 *	0.020	1	
Ca	−0.186	−0.886 **	−0.462 **	−0.703 **	0.327 **	0.114	1

Note: ** and * denote significance levels of 0.01 and 0.05, respectively.

3.4.2. Correlation Analysis of Plant Carbon Sequestration and Oxygen Release Capacity with Morphological Indicators

The study examined the relationship between the carbon sequestration and oxygen release capacities of 13 plant species and their morphological indicators. Table 5 presents the findings, which indicate that there was no significant correlation between the carbon sequestration and oxygen release capacity per unit leaf area, as well as other morphological factors such as plant height, diameter at breast height, crown area, LAI, SLA, and stand density. However, the study did find a positive correlation between the carbon sequestration and oxygen release capacities of individual plants with their height ($p < 0.01$) and diameter at breast height ($p < 0.05$). Furthermore, the oxygen and carbon sequestration capacity per unit land area showed a positive correlation with planting density ($p < 0.01$).

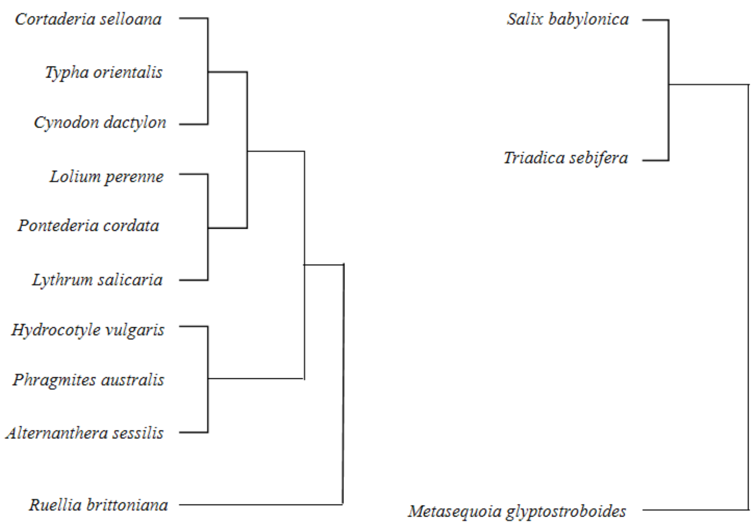
Table 5. Correlation analysis between plant carbon sequestration and oxygen release capacity and plant morphological indicators.

	Plant Height	Plant Diameter at Breast Height	Plant Crown Area	Leaf Area Index	Specific Leaf Area	Planting Density	Oxygen Sequestration Per Unit Leaf Area	Oxygen Sequestration Per Plant	Oxygen and Carbon Sequestration Per Unit of Land Area
Plant height	1								
Plant diameter at breast height	0.886 **	1							
Plant crown area	0.811 **	0.862 **	1						
Leaf area index	0.817	0.490	0.348	1					
Specific leaf area	−0.803 *	−0.821 *	−0.879 **	−0.662	1				
Planting density	−0.581	−0.341	−0.436	−0.458	0.395	1			
Oxygen sequestration per unit leaf area	0.131	−0.218	−0.312	−0.102	−0.515	0.098	1		
Oxygen sequestration per plant	0.878 **	0.832 *	0.773	0.566	−0.621	−0.333	0.163	1	
Oxygen and carbon sequestration per unit of land area	0.620	0.327	−0.013	0.762	−0.448	0.975 **	−0.089	0.471	1

Note: ** and * denote significance levels of 0.01 and 0.05, respectively.

3.5. Cluster Analysis of Plant Carbon Sequestration and Oxygen Release Capacity

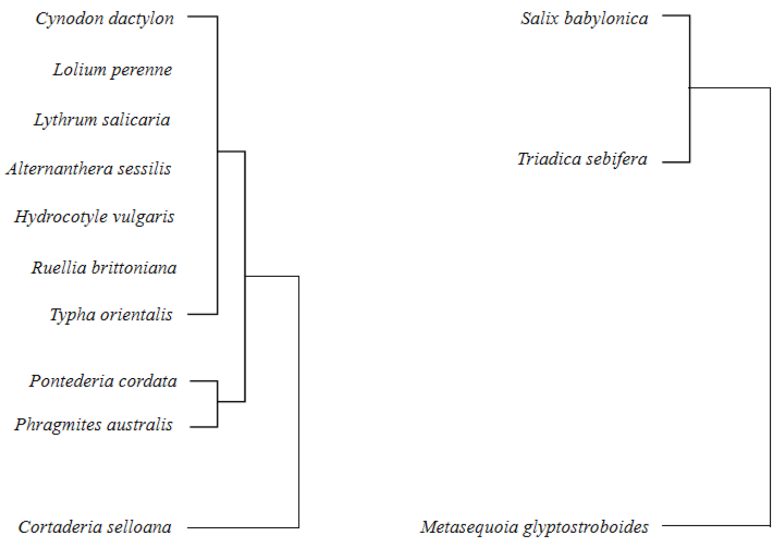
According to the cluster analysis shown in Figure 6, the oxygen sequestration capacity per unit leaf area of 10 herbaceous plants and 3 trees was examined. The analysis revealed that the 10 herbaceous plants could be categorized into three levels. *Ruellia brittoniana* exhibited the highest oxygen sequestration capacity per unit leaf area and was classified as the first level. The second level included *Cortaderia selloana*, *Typha orientalis*, and *Cynodon dactylon*, which had a moderate capacity for oxygen sequestration per unit leaf area. *Hydrocotyle vulgaris*, *Phragmites australis*, *Alternanthera sessilis*, *Lolium perenne*, *Pontederia cordata*, and *Lythrum salicaria* were classified as the third level, indicating a weak capacity for carbon and oxygen sequestration per unit leaf area. The three tree species were categorized into two classes. *Metasequoia glyptostroboides* exhibited a strong oxygen sequestration capacity per unit leaf area and was classified as the first level, while *Salix babylonica* and *Triadica sebifera* were classified as the third level with a weak oxygen sequestration capacity per unit leaf area.



(**a**) Herbaceous (**b**) Trees

Figure 6. Cluster analysis of plant carbon sequestration and oxygen release capacity per unit leaf area.

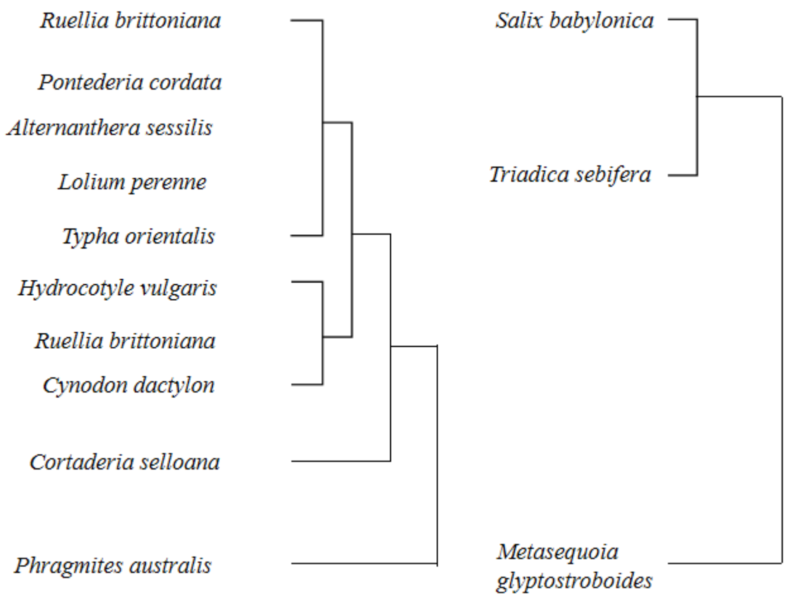
According to the cluster analysis of the oxygen sequestration capacity of plants (shown in Figure 7), 10 herbaceous plants were classified into three levels. *Cortaderia selloana* had the highest oxygen sequestration capacity and was classified as the first level. *Pontederia cordata* and *Cortaderia selloana* were classified as the second level with a moderate oxygen sequestration capacity. *Cynodon dactylon*, *Lolium perenne*, *Lythrum salicaria*, *Alternanthera sessilis*, *Hydrocotyle vulgaris*, *Ruellia brittoniana*, and *Typha orientalis* were classified as the third level with a weaker oxygen sequestration capacity. Among the three species of trees, *Metasequoia glyptostroboides* was categorized as the first level, having a strong capacity for carbon sequestration and oxygen release by single plants. *Salix babylonica* and *Triadica sebifera* were classified as the second level, with a weaker capacity for carbon sequestration and oxygen release by single plants.



(**a**) Herbaceous (**b**) Trees

Figure 7. Cluster analysis of carbon sequestration and oxygen release capacity of single plants.

According to Figure 8, the cluster analysis of the oxygen sequestration capacity per unit land area of each plant resulted in the classification of 10 herbaceous plants into three levels. *Phragmites australis* is classified as the first level, exhibiting the strongest oxygen sequestration capacity per unit land area. *Cortaderia selloana* is classified as the second level, with a medium oxygen sequestration capacity per unit land area. *Lythrum salicaria*, *Pontederia cordata*, *Alternanthera sessilis*, *Lolium perenne*, *Typha orientalis*, *Hydrocotyle vulgaris*, *Ruellia brittoniana*, and *Cynodon dactylon* are classified as the third level, with a weaker oxygen sequestration capacity per unit land area. On the other hand, the three species of trees can be divided into two classes. *Metasequoia glyptostroboides* is classified as the first level, demonstrating a strong capacity for sequestering carbon and releasing oxygen per unit land area. *Salix babylonica* and *Triadica sebifera*, on the other hand, are classified as the second level, with a weaker capacity for sequestering carbon and releasing oxygen per unit land area.



(**a**) Herbaceous (**b**) Trees

Figure 8. Cluster analysis of plants' capacity to sequester carbon and release oxygen per unit land area.

4. Discussion

4.1. Changing Pattern of Daily Net Photosynthetic Rate of Riparian Zone Plants

Numerous scholars have conducted extensive research on the carbon sequestration and oxygen release capacity of plants in various regions and environments. Pn is a crucial indicator that directly impacts a plant's ability to sequester carbon and release oxygen. Plants with a high NPV can efficiently fix carbon dioxide, convert it into organic matter, and release more oxygen. The NPV of 13 plant species displayed different daily change curves and peak values, which were classified into single-peak and double-peak types. The single-peak type included *Hydrocotyle vulgaris* and *Cynodon dactylon*, etc., while the double-peak type included *Typha orientalis* and *Lythrum salicaria*, etc. Generally, Pn was lower in the morning and evening and higher at noon. This is because the light intensity is relatively low in the morning and evening but reaches its peak at noon, allowing plants to fully utilize light energy for photosynthesis. This is consistent with the findings of Ghasemzadeh [19] that the Pn of plants was lower during the morning and evening hours when light conditions were weak and higher during the midday hours when light intensity was the highest. The bimodal curves observed in plants can be attributed to the phenomenon of a "photosynthesis lunch break". During the summer, when light intensity is strongest at noon, plants close their stomata to retain water. However, this stomatal closure reduces the availability of CO_2 for the plants, which affects CO_2 fixation in the dark reaction and subsequently reduces photosynthesis. This is consistent with the results reported by Maai [20]. Additionally, this study found that herbs generally exhibited higher daily net photosynthetic rates compared to trees, with *Ruellia brittoniana* having the highest maximum Pn and *Triadica sebifera* having the lowest. These findings are in line with the research conducted by Chu [21] on the daily Pn of common greening plants in east subtropical China, which found that the rate of herbs was higher than that of trees.

Pn of plants vary not only at regional and environmental scales but also due to their own physicochemical properties [22]. Leaves serve as the medium for energy exchange between soil–plant and atmosphere. LAI is commonly used to assess the sparseness and density of vegetation leaves, which is crucial for evaluating physiological and physical processes such as photosynthesis, respiration, and transpiration [23]. In this study, *Metasequoia glyptostroboides* exhibited significantly higher leaf area per plant, leaf dry weight per plant, and LAI compared to other plants. Trees also had significantly higher values than herbs, indicating that *Metasequoia glyptostroboides* had better light acceptance, photosynthetic utilization, and productivity. This finding aligns with previous research by Kahiu [24], which observed that among the 10 typical plant species of dry-season savannas and humid tropical forests in Africa, LAI of trees was greater than that of herbaceous plants. SLA is often used to assess plant growth response, light capture ability, and adaptability to environmental changes. In this study, herbs had slightly higher SLA than trees. These results are consistent with the findings of Zhao [25], who reported that herbs had a higher specific leaf area than trees in all growth stages among 68 different functional groups of plants in the Maolan karst area.

4.2. Analysis of Carbon Sequestration and Oxygen Release Capacity of Riparian Zone Plants

The study evaluated the carbon and oxygen sequestration capacities of 13 different plant species. The results showed that *Ruellia brittoniana* had the highest performance in terms of oxygen sequestration and release per unit of leaf area among the herbaceous plants. *Typha orientalis*, *Cortaderia selloana*, and *Cynodon dactylon* also exhibited high oxygen sequestration and release per unit of leaf area. On the other hand, *Hydrocotyle vulgaris* and *Alternanthera sessilis* had relatively weaker oxygen sequestration and release capacities. The three tree species showed lower levels of oxygen sequestration and release per unit of leaf area compared to the herbaceous plants. These findings align with Feng's [13] study, which concluded that herbs have significantly higher carbon sequestration and oxygen release capacities per unit of leaf area than trees. *Metasequoia glyptostroboides*, *Salix babylonica*, and *Triadica sebifera* demonstrated much higher oxygen sequestration capacities per plant, while *Cynodon dactylon* and *Lolium perenne* showed the weakest capacities. This can be attributed to the larger leaf area of trees, enabling them to receive more solar energy and photosynthesize more efficiently. Additionally, the study found that trees exhibited a higher oxygen sequestration capacity per unit of land area compared to other plants, which is consistent with the findings of Xiong's [26] research on 17 commonly used greening plants in the urban-rural interface of Beijing.

4.3. Analysis of Factors Affecting Oxygen Sequestration Capacity of Plants in Riparian Zones

The correlation analysis of this study revealed that the daily carbon sequestration and oxygen release capacity per unit leaf area of plants were positively correlated with PAR, Ti, RH, and Ta. This is because the daily carbon sequestration and oxygen release capacity per unit leaf area was calculated based on the daily net photosynthesis rate, which is a physiological and biochemical process influenced by PAR, temperature, and humidity. These factors also affect the stomatal conductance of leaves. These findings are consistent with the results of a previous study by Du [27] on stomatal morphology and photosynthetic characteristics of tomatoes were consistent. Additionally, the study found a significant positive correlation between the daily oxygen and carbon sequestration capacity of a single plant and its plant height and diameter. This correlation was particularly strong between plant height and the oxygen and carbon sequestration capacity of a single plant. Generally, the daily carbon sequestration and oxygen release capacity of a single plant is directly proportional to its own biomass, with plant height and diameter at breast height being key factors determining the carbon sequestration capacity. Furthermore, the study found a positive correlation between the daily carbon sequestration and oxygen release capacity per unit of land area and planting density. This finding is consistent with the result of a study by Liu [28], which showed that higher silvicultural density in poplar plantation forests enhances oxygen sequestration. Pn in this study had a low one-factor correlation coefficient because it was affected by a number of complex factors. However, even with low correlation coefficients, they still provide valuable information about the relationship of the variables. Low correlation coefficients may suggest potential trends or patterns that contribute to the understanding of the study system [29].

5. Conclusions

In this study, we investigated the daily carbon sequestration and oxygen release capacities of 13 typical riparian zone plants in the middle section of small and medium-sized rivers in Wuhan. We also examined the factors that influence these capacities. Our findings revealed variations in the oxygen sequestration capacity among different plants at different scales. Trees exhibited higher oxygen sequestration capacity compared to herbaceous plants in both individual plant and unit land area scales. Notably, *Metasequoia glyptostroboides* demonstrated the highest oxygen sequestration capacity among trees, while *Phragmites australis*, *Cortaderia selloana*, and *Cynodon dactylon* showed particularly prominent capacity among herbaceous plants. Therefore, for future ecological restoration projects in Wuhan City, priority should be given to planting *Metasequoia glyptostroboides*, as well as herbaceous plants like *Phragmites australis*, *Cortaderia selloana*, and *Cynodon dactylon*, which have better carbon sequestration and oxygen-releasing capacities. This approach will help enhance the carbon sequestration and oxygen-releasing capacities of riparian vegetation, leading to greater ecological benefits.

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