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EDITED BY
Wenjie Wang,
Northeast Forestry University, China

REVIEWED BY
Dan Zhang,
Changchun University, China
Rattanawat Chaiyarat,
Mahidol University, Thailand

*CORRESPONDENCE
Qing Zhao
zhaoqing@sinogaf.cn

†These authors have contributed equally to this work

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Growth patterns and environmental adaptions of the tree species planted for ecological remediation in typhoon-disturbed areas—A case study in Zhuhai, China

Chi Zhang†, Wanhui Qian†, Lei Song and Qing Zhao*

Guangdong Provincial Key Laboratory of Silviculture Protection and Utilization, Guangdong Academy of Forestry, Guangzhou, China

Typhoon frequently results in various mechanical damages to urban forest ecosystems. Imperative forest remediation projects were launched to restore the environmental conditions in cities, in which massive trees were newly planted. However, it was rarely answered whether the newly planted trees could acclimate to typhoon circumstances and enhance the wind resistance of the local ecosystem. Therefore, it was necessary to achieve information on the physical growth and windy environmental adaption of newly planted trees, which could promote a profound understanding of the efficiency of post-typhoon ecological remediation. In this study, we selected Zhuhai's urban-forest remediation district as our research area that suffered severely from Typhoon Hato (2017). The six newly-planted tree species for the ecological remediation were measured for their above- and below-ground processes from June 2018 to December 2019, including their development of tree height, ground diameter, crown size, and fine root biomass. Additionally, the variations of the soil's physical and chemical properties were also measured to assess the impact of plantation on soil conditions. Our results showed that the six surveyed tree species had different above- and below-ground growth patterns. With robust root development at horizontal and vertical levels combined with relatively short and thick above-ground profiles, *Sterculia lanceolata* Cav. and *Cinnamomum camphora* (Linn) were likely to cope well with typhoon disturbances. *Ilex rotunda* Thunb. and *Schima superba* Gardn. et Champ. exhibited moderate acclimation to windy environment, while *Elaeocarpus sylvestris* (Lour.) Poir. and *Elaeocarpus apiculatus* Mast. were not recommended to be planted in typhoon-disturbed areas concerning their unstable root development. In addition, the ecological remediation did improve the soil properties, specifically for the chemical characteristics including available nitrogen, available potassium, and soil organic matter. To improve the effectiveness of forest remediation in the future, it was better to choose those tree species with vigorous root development and steady values of root:shoot ratios, which might be advantageous for coping with typhoon disturbances.

The tree species with prosperous above-ground growth were not suitable for areas facing strong winds directly but could be planted in leeward regions to amplify their landscape functions.

KEYWORDS

forest management, root growth, soil properties, typhoon events, urban tree species

Introduction

The past decades have witnessed robust evidence that global change was progressively affecting human society and natural ecosystems, accompanying increasing intensity and frequency of extreme climatic events altering ecosystem structures and functions well outside normal variability (Altman et al., 2013; Tollefson, 2018). Combined with the fast-growing urbanization, typhoon events in coastal cities had caused enormous economic loss and ecosystem's severe degradation, which had emphasized the demand for extensive attention and profound understanding (Zhang et al., 2021). Currently, most relevant researches were conducted from meteorological perspectives. For instance, the dynamic variations, affected regions, and impacts on precipitation of typhoon events were analyzed from 1957 to 1996 in China (Thuan et al., 2016). Zhou et al. (2022) quantified the storm precipitation, flooding, landslides, and weather services caused by typhoon events and subsequent effects on urban habitants. In addition, how typhoons and hurricanes exerted impacts on coastal ecosystems were also investigated, e.g., wetlands, lakes, and forests (Lin et al., 2011; Ding et al., 2012; Wang et al., 2016).

Although various studies provided plentiful information on the origins, paths, and intensities of typhoons, the knowledge of the efficiency of post-typhoon ecological remediation remained scarce. Generally, ecological remediation aimed to restore environmental conditions to the status before disturbances occurred (Ceccanti et al., 2006; Xu et al., 2019), however, whether the multiple operations adopted could leave a long-term effect that the ecosystem was strengthened for coping with similar disturbances in the future. For example, in typhoon-effect areas where the local urban forest ecosystem experienced severe disturbances with substantial trees being broken off or lodged, the ecological remediation projects mainly focused on the new plantation of trees and their survival rates. Nonetheless, it might not be thoroughly answered whether the planted trees could improve the resistance of the local ecosystem against windy stress, which could result in an absence of information regarding the efficiency and effectiveness of the ecological remediation (Duryea et al., 2007). For instance, as a city suffering from frequent typhoon events in the past decades, Zhuhai of China planted massive trees after strong typhoon left. However, information on the growth, adaption, and ecosystem services of the newly-planted trees remained scarce that led to an ambiguous understanding of the quality of the ecological remediation, probably exposing the city to typhoon disturbances again and causing exponentially increasing economic losses associated with rising numbers of injuries. Therefore, comprehensive investigations in the trees for the ecological remediation could be positive efforts for making valuable recommendations in typhoon-suffering regions at a long-term scale.

Urban trees, playing a crucial role in recovering soil fertility, water conservation, and providing landscape functions, could be a key component in maintaining ecological balances of cities (Diemont et al., 2006; Roy et al., 2012). In particular, their development of below-ground processes reflected not only the health conditions but also their adaption to extreme climatic events, which was considered to be the fundamental part of the local forest ecosystems under various disturbances. For example, Schenk proposed that the rooting profiles of plant communities could be adjusted due to various stresses, such as the construction of deep roots could be invested more to deal with drought stress (Schenk, 2008). Stratópoulos et al. noted that tree species had different strategies for below-ground growth and root:shoot ratios to adapt to the changing environment (Stratópoulos et al., 2019). Moreover, it was noticed that the fine root development had pivotal importance for trees' supplying multiple ecosystem services, especially for ecological remediation against typhoon disturbances (Zhang et al., 2021). Consequently, comprehensive knowledge of trees' growth patterns could contribute potently to a profound understanding of their physiological statuses and ecosystem services, which also promoted the clarification of the efficiency of forest remediation.

In 2017, Typhoon Hato intruded on Zhuhai and severely affected the local forest ecosystem. After that, the local administrative department implemented imperative ecological remediation through a massive plantation of trees. This remediation was conducted mostly from administrative perspective as before, lacking the knowledge of the detailed development of planted trees. To promote our recognition of the efficiency of the ecological remediation and provide suggestions and guidance for urban forest management in the future, we selected the remediation district encountering Typhoon Hato as our objected area and established observation experiments for the newly-planted tree species from June 2018 to December 2019. For each tree species, their above-ground and below-ground development were measured and the root:shoot ratios were also analyzed to assess their biomass allocation strategies. Additionally, with environmental data, we expected to answer questions as follows: (1) whether did the newly-planted trees adapt to the local environment regarding their growth patterns? (2) How did the surveyed tree species develop their fine root biomass at vertical and horizontal levels? (3) Under the ecological remediation, was the soil condition improved in terms of physical and chemical properties? (4) What kind of tree species could be recommended in typhoon-affected areas?

Materials and methods

Study area, tree species, and sampling plots

With a population of 2.43 million and an urbanization rate of 90.7%, Zhuhai is a rapid-developing city situated in one of the most developed special economic zones in China (Sheng and Tang, 2013). Meanwhile, as a coastal city adjacent to China South Sea under marine climate, Zhuhai encounters frequent typhoon events and confronts substantial economic losses (Yang et al., 2019). After each typhoon left, the forests and trees in Zhuhai were disturbed in multiple forms, e.g., whole-tree lodging, stems' breaking down, branches' bending or breaking off, and roots' tearing up, which had various negative influences on the local ecosystem and biodiversity. On 20th August 2017, Typhoon Hato was generated on the northwestern Pacific Ocean and constantly intensified within 72 hours. At 12:50 on 23rd August, it landed on Zhuhai at wind scale 14 and moved forward in the northwest direction (Figure 1). During its route in Zhuhai lasting over 4 h, more than 25% of urban trees in Zhuhai were damaged by the strong wind (Zhang et al., 2021). After the typhoon left, the local administrative department implemented imperative ecological remediation in typhoon-affected areas. Heibaimian Mountain, severely suffering from wind damages following massive plantation of seedlings for ecological remediation, was chosen for our study area. In this area, the most planted tree species were: *Sterculia lanceolata* Cav. (*Sl*), *Ilex rotunda* Thunb. (*Ir*), Schima superba Gardn. et Champ. (*Ss*), *Cinnamomum camphora* (Linn) Presl (*Cc*), *Elaeocarpus sylvestris* (Lour.) Poir. (*Es*), and *Elaeocarpus apiculatus* Mast. (*Ea*) and the seedlings were planted in 3 m × 3 m. All the planted seedlings of the six tree species were 1 year old with very small initial sizes. To investigate their growth and ecosystem services, ten sampling plots with the size of 20 m × 20 m were established randomly in the study area. In each sampling plot, all the trees were surveyed for tree height and ground diameter [because newly-planted seedlings were too small for DBH measurements (diameter at breast height)], based on which ten representative sampling trees of each tree species were determined, i.e., overall 60 trees. For them, both above- and below-ground measurements were launched for 18 months, which were conducted in December 2018, June 2019, and December 2019, i.e., trees' ages in the 6th month, 12th month, and 18th month.

Meteorological variables

Climate data was supplied and calibrated by the National Meteorological Information Center of China (2022), based on which monthly variables including Vapor Pressure Deficit (VPD, hPa), wind velocity (km h^{-1}), precipitation (mm), and temperature (°C) were collected and calculated from January 2017 to December 2019 in Zhuhai (Figure 2). From the historical meteorological data from 1995 to 2015, Zhuhai had a relatively high average temperature of 22.5°C and abundant precipitation of over 2000 mm annually. The annual average temperature and precipitation were 23.4°C and 1942 mm together with a moderate mean wind velocity fluctuating around 10 km h^{-1} from 2017 to 2019. In August 2017, Typhoon Hato landed in the southeast coastal areas of China and intruded the front of Zhuhai city, resulting in the monthly highest wind velocity and precipitation reaching 217 km h^{-1} and 277 mm, which indicated a swift and dramatic change of the local weather conditions.

Measurement of soil conditions

The primary soil type in Zhuhai is mahogany red soil. The soil sampling campaign was launched in the study area in June 2018 and December 2019 to indicate the development of soil's physical and chemical properties. Each time ten metallic-cylindrical sampling cores were used to dig out four kilograms of soil at the depth of 30 cm, which were randomly located in the study area same as the sampling plots. Then all the soil samples were well kept in sampling bags and transported to our laboratory for further analysis. The soil's physical properties were measured according to Li and Shao's reports (Li and Shao, 2006). Soil bulk densities (*BD*, g cm^{-3}) were determined by the mass of soil per unit volume (sum of solids and pore space) and the soil cores were oven-dried at 105°C to obtain soil moisture content (*SMC*, %). Then, the soil cores were put on a sand salver and allowed to drain for 2 h in order to calculate soil capillary water content (*Scwc*). Hence, soil capillary porosity (*Scp*, %) was calculated according to the equation as:

$$Scp = 0.1 \times Scwc \times ds$$

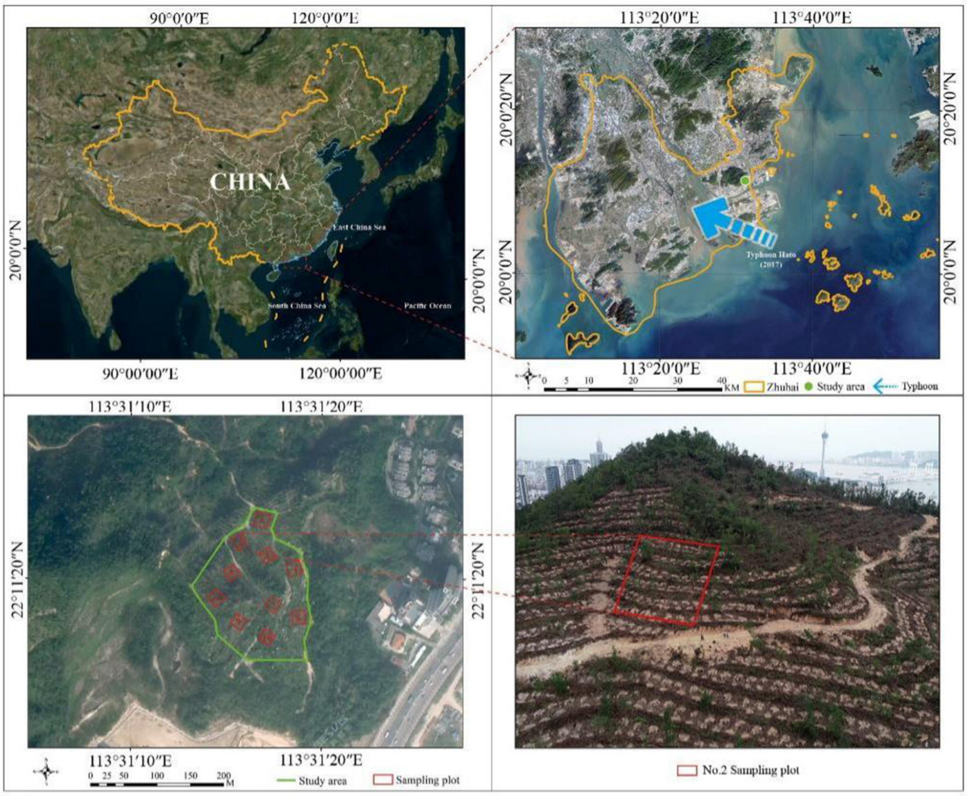

FIGURE 1
Schematic location of Zhuhai in China **(top left)**, Typhoon Hato' route and study area in Zhuhai **(top right)**, sampling plots in the study area **(bottom left)**, and the No.2 sampling plot **(bottom right)**.

where *ds* is the soil density (mg m^{-3}). And soil non-capillary porosity (*Sncp*, %) and soil total porosity (*Stp*, %) were calculated as:

$$Sncp = 0.1 \times (Smc - Scwc) \times ds$$
$$Stp = Scp + Sncp$$

For soil chemical properties, soil *pH* was determined in 1:2.5 soil-water slurry using a combination glass electrode. Soil organic matter (*SOM*, g kg^{-1}) was determined by the oil bath-$K_2Cr_2O_7$ titration method. Total nitrogen (*TN*, g kg^{-1}) was determined by the semi-micro Kjeldahl method. Available nitrogen (*AN*, mg kg^{-1}) was determined by a micro-diffusion technique after alkaline hydrolysis. Total phosphorus (*TP*, g kg^{-1}) was determined colorimetrically after wet digestion with $H_2SO_4 + HClO_4$. Available phosphorus (*AP*, mg kg^{-1}) was exacted with 0.5 mol l^{-1} $NaHCO_3$ solution (*pH* 8.5). Total potassium (*TK*, g kg^{-1}) was determined by the Cornfield method. Available potassium (*AK*, mg kg^{-1}) was determined by the CH_3COONH_4 extraction method (Liu et al., 1996).

Measurement and calculation of above-ground development

To investigate the above-ground growth of the six tree species, their ground diameter, tree height, and *LAI* (leaf area index) were measured in the 6, 12, and 18th month. Ground diameters were measured with the help of a caliper (Altraco Inc., Sausalito, California, USA) and their heights were measured using a standard tape. The crown analytical instrument CI-110 (Camas, Washington State, USA) was used to capture the accurate image of tree crowns and calculate *LAI*. Sufficient numbers of points were measured and recorded to describe each of the trees' average crown shape and software FV2200 (LICOR Biosciences, Lincoln, NE) helped to compute the projected crown area (*PCA*) of each tree.

SLA (specific leaf area) was calculated as the ratio of leaf area to leaf dry mass (m^2 g^{-1}) (Zhang et al., 2019). In December 2019, an overall harvest campaign of leaves was launched for the six tree species. For all the leaves, we made random selections in four frequencies of numbers, i.e., 20-, 40-, 60-, and 80-leaves. All the frequencies were repeated for three times and the selected leaves were scanned for their areas and dried for their dry mass.

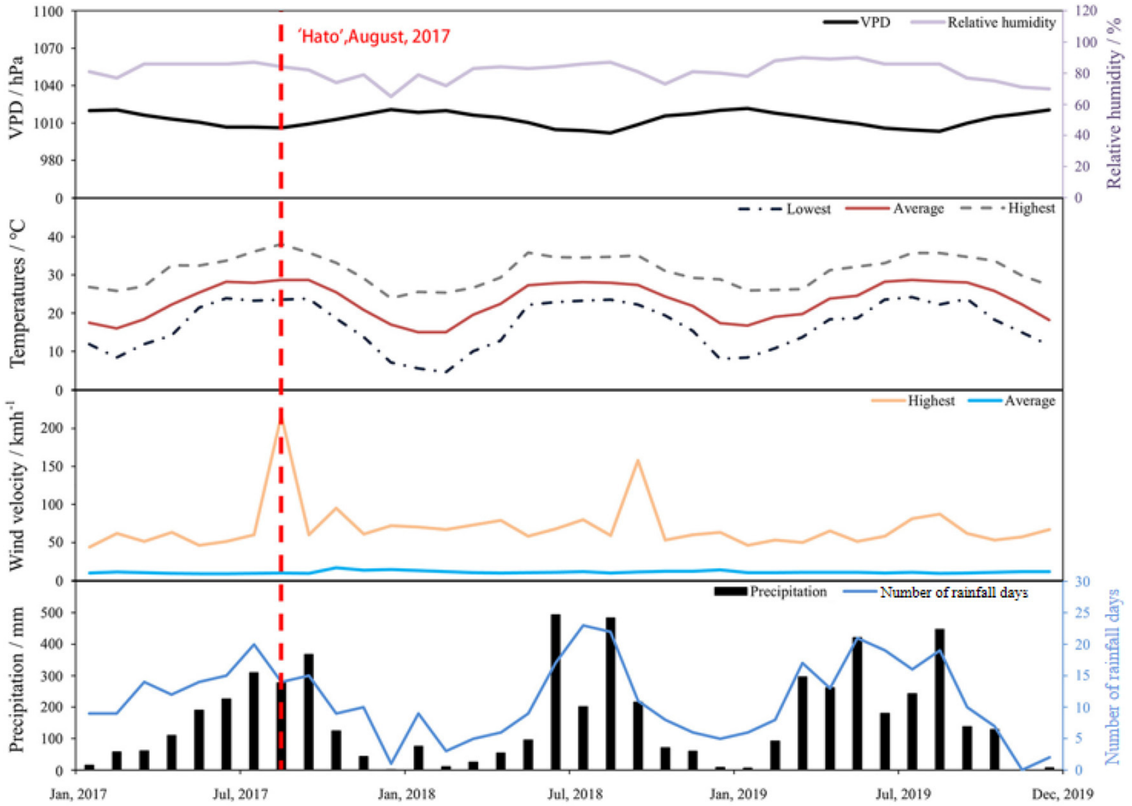

FIGURE 2
Monthly climate variables, including highest wind velocities (km h^{-1}), average wind velocities (m s^{-1}), precipitation (mm), number of rainfall days, highest temperature (°C), mean temperature (°C), and lowest temperature (°C) for Zhuhai from January 2017 to December 2019. The vertical-red-dotted line indicates when Typhoon Hato arrived at Zhuhai city.

Thus, the weighted averaged *SLA* was calculated as the ratios of single leaf's area and single leaf's dry weight, and the leaf biomass of all the six tree species was calculated combined with *LAI*, *SLA*, and *PCA* as follows:

$$Biomass_{leaf} = \frac{LAI * PCA}{SLA}$$

Measurement and calculation of below-ground development

To clarify the below-ground progress, fine root coring campaigns were launched for all the selected trees in the 6, 12, and 18th month. In this study, considering the tree pit was 0.5 m × 0.5 m × 0.4 m (length × width × depth), we set two soils collection in each direction of north, south, east, and west, that one was located at 15 cm to the trunk for inner roots and the other one was located at 30 cm for outer roots. In addition, the soil samples were divided into three horizons: 0–10 cm (upper layer), 10–20 cm (middle layer), and 20–30 cm (deep layer). Fine roots from all the soil samples (<2 mm) were filtered using sieves (2-mm mesh size) and separated by forceps in the laboratory. Then, the samples were washed and dried in an oven at 65°C for 72 h. Finally, all the samples were weighed using a balance with an accuracy of four decimal places to obtain the dry weight. The fine root biomass at different depths was calculated using the dry weight divided by the cross-sectional area of the auger. Generally the root:shoot ratio was calculated by harvest, however, the trees in this research were all prevented from harvest. Therefore, the root:shoot ratios in this study were inferred by the ratios of fine root biomass and leaf biomass as follows:

$$Root : shoot\ ratio = \frac{Biomass_{fine\ root}}{Biomass_{leaf}}$$

Statistical analyses

The software SPSS 22.0 (IBM, State of New York, USA) was used for statistical analyses. To investigate the difference between means, two-sampled *t*-test and analysis of variance

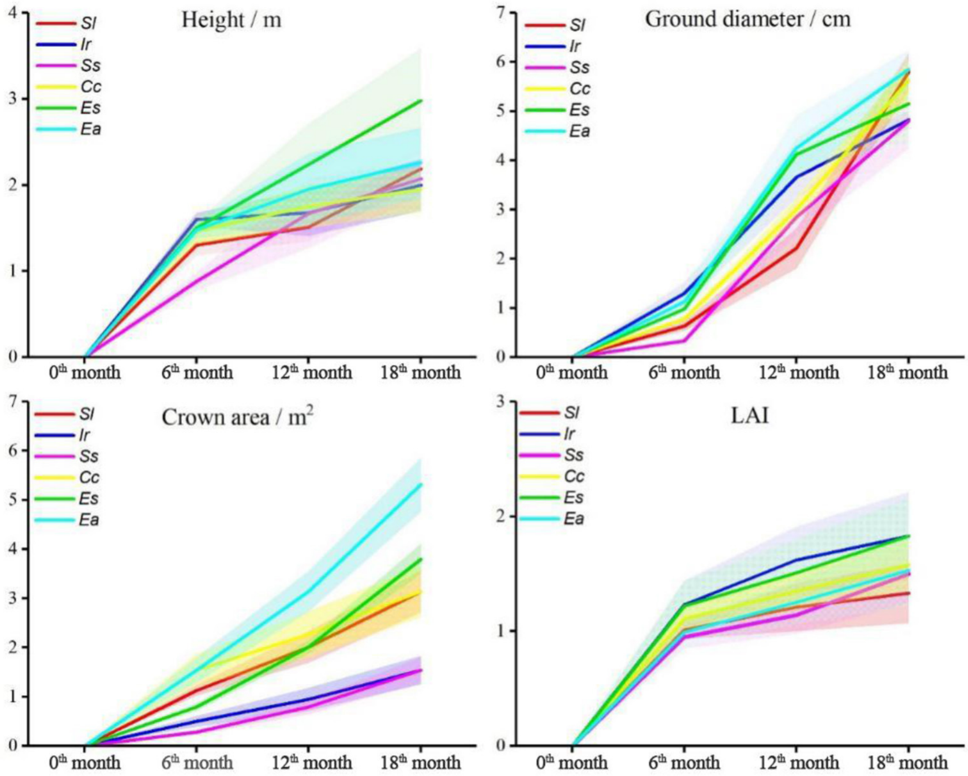

FIGURE 3
Development of tree height (m), ground diameter (cm), crown area (m^2), and LAI of all the six tree species from the 0 to 18th month since plantation. The abbreviations of *Sl*, *Ir*, *Ss*, *Cc*, *Es*, and *Ea* were short for *Sterculia lanceolata*, *Ilex rotunda*, *Schima superba*, *Cinnamomum camphora*, *Elaeocarpus sylvestris*, and *Elaeocarpus apiculatus*. Around *Sl* (red line), *Ir* (cyan line), *Ss* (red-purple line), *Cc* (yellow line), *Es* (green line), and *Ea* (light blue line), the light shading areas are the 95% confidence intervals, respectively.

(ANOVA) with Tukey's HSD (honestly significant difference) test were used. In all the cases, the means were reported as significant when $P < 0.05$. Where necessary, data were log or power transformed in order to correct for data displaying heteroscedasticity.

Results

Development of above-ground process

The six tree species exhibited different growth patterns in tree height, ground diameter, crown area, and *LAI* within the whole period of 18 months (Figure 3).

In terms of tree height, *Es* reached 2.98 m in the 18th month, which was way higher than others. The other five tree species had relatively lower values in the 18th month (*Sl*: 2.19 m; *Ir*: 2.00; *Ss*: 2.07 m; *Cc*: 1.95 m; *Ea*: 2.26 m), however, they had different predominant growth periods. *Sl*, *Ir*, *Cc*, and *Ea* had main substantial development from the 0 to 6th month, and showed a distinct deceleration from the 6 to 12th month. On the contrary, *Ss* maintained sharp growth from the 0 to 12th month (from 0 m to 1.67 m), while exhibited gentle growth from the 12 to 18th month (from 1.67m to 2.07 m).

For ground diameter, *Sl* and *Ea* had distinct advantages (*Sl*: 5.80 cm; *Ea*: 5.85 cm) while *Ir* and *Ss* showed lowest values (*Ir*: 4.83 cm; *Ss*: 4.80 cm). Additionally, the swift growth of *Ir*, *Ss*, *Es*, and *Ea* mainly occurred in the period from the 6 to 12th month (*Ir*: from 1.30 cm to 3.66 cm; *Ss*: 0.33 cm to 2.85 cm; *Es*: from 0.98 cm to 4.12 cm; *Ea*: from 1.13 cm to 4.25 cm), while *Sl* and *Cc* displayed a continuously accelerated growth pattern from the whole observation period of 18 months.(*Sl*: 0.63 cm, 2.21 cm, 5.80 cm in the 6, 12, and 18th month; *Cc*: 0.78, 3.00, 5.63 cm in the 6, 12, and 18th month).

Regarding crown area, the six tree species exhibited development with different velocities of increase. From the 0 to 18th month, *Ea* had the highest values all the times (1.54 m^2 in the 6th month; 3.14 m^2 in the 12th month; 5.31 m^2 in the 18th month). In the 18th month, *Sl* and *Cc* had the medium values (*Sl*: 3.14 m^2; *Cc*: 3.14 m^2) while *Ir* and *Ss* displayed obvious disadvantages (*Ir*: 1.54 m^2; *Ss*: 1.54 m^2). For *Es*, the growth behaved differently from other tree species that a moderate growth occurred from the 0 to 12th month, while in the next

TABLE 1 Overall fine root biomass (g m^{-2}) with standard deviations of all the six tree species from the 6 to 18th month since plantation.

Tree species	*n*	Overall fine root biomass (g m^{-2} ± SD)		
		6th month	12th month	18th month
Sl	10	19.64 ± 17.92[a]	229.06 ± 136.12[a]	269.36 ± 163.18[a]
Ir	10	21.81 ± 18.49[a]	290.64 ± 133.99[a]	240.06 ± 119.40[a]
Ss	10	11.20 ± 13.17[b]	244.43 ± 143.74[a]	215.70 ± 137.11[a]
Cc	10	17.18 ± 19.27[a]	271.46 ± 117.40[a]	256.63 ± 149.94[a]
Es	10	21.38 ± 25.68[a]	415.63 ± 184.29[b]	248.52 ± 136.73[a]
Ea	10	31.11 ± 31.58[a]	415.72 ± 183.60[b]	342.80 ± 230.33[b]

The abbreviations of *Sl*, *Ir*, *Ss*, *Cc*, *Es*, and *Ea* were short for Sterculia lanceolata, Ilex rotunda, Schima superba, Cinnamomum camphora, Elaeocarpus sylvestris, and Elaeocarpus apiculatus. The letters "a" and "b" indicate significant differences ($P < 0.05$) between the biomass of different tree species in the same month.

6 months it had a strong development which reached the second highest level among all the six tree species (3.8 m^2).

For *LAI*, the six tree species showed similar development patterns from the 0 to 18th month. The major difference existed in their growing rates. In the 18th month, *Ir* had the highest value (1.84), followed by *Es* (1.83). *Ss*, *Cc*, and *Ea* had moderate values (*Ss*: 1.50; *Cc*: 1.58; *Ea*: 1.53), while *Sl* had the lowest one (1.33).

Development of below-ground process

Table 1 gives the detailed information on the overall fine root biomass of the six surveyed tree species from the 6 to 18th month. Compared to the slight growth from the 0 to 6th month, all the tree species had remarkable increase from the 6 to 12th month ($P < 0.05$), e.g., *Sl* (from 19.64 g m^{-2} to 229.06 g m^{-2}), *Ss* (from 11.20 g m^{-2} to 244.43 g m^{-2}), *Es* (from 21.38 g m^{-2} to 415.63 g m^{-2}). Nevertheless, except for *Sl* maintaining steady growth from 229.06 g m^{-2} to 269.36 g m^{-2}, the other five tree species exhibited an abnormal decrease from the 12 to 18th month, of which *Es* and *Ea* had a significant reduction (*Es*: from 415.63 g m^{-2} to 248.52 g m^{-2}; *Ea*: from 415.72 g m^{-2} to 342.80 g m^{-2}).

The vertical development of fine root biomass, i.e., fine root biomass in the shallow layer (0–10 cm), middle layer (10–20 cm), and deep layer (20–30 cm), was given below (Figure 4). In the 6th month, the six tree species mainly had shallow fine roots, however, they obtained dramatic increases for all the three layers from the 6 to 12th month, e.g., *Ir*'s shallow layer (from 20.00 g m^{-2} to 122.93 g m^{-2}), *Cc*'s middle layer (from 5.41 g m^{-2} to 88.66 g m^{-2}). In the 12th month, significant higher values of fine root biomass were found for *Es*' middle and deep layer as well as *Ea*'s middle layer. From the 12 to 18th month, except for *Sl*'s consistent increases in all the three layers, the other five tree species displayed different patterns. Besides, fine root biomass of *Sl*'s shallow layer and *Ea*'s deep layer was significantly greater than the same layer of other tree species, indicating their special strategy in vertical level. For *Ir*, *Ss*, *Cc*, and *Ea*, the roots in the layer of 0–10 and 10–20 cm showed biomass decreases, e.g., *Ir*'s shallow and middle layer reduced from 122.93 and 103.17 g m^{-2} to 91.39 and 81.35 g m^{-2}, whereas their deep roots in the layer of 20–30 cm obtained increases such as *Ss* (from 25.14 to 42.37 g m^{-2}) and *Ea* (from 74.74 to 123.66 g m^{-2}). A complete decline of all the layers was detected for *Es* that the three groups of 0–10, 10–20, and 20–30 cm decreased from 164.39, 158.97, and 92.27 to 86.66, 92.53, and 69.33 g m^{-2}, respectively.

Fine root biomass located from 15 cm to tree trunks (inner roots) and from 30 cm to tree trunks (outer roots) provided us with a perspective on the root's horizontal development (Figure 5). In the 6th month, no significant difference was found between the inner and outer fine root biomass of the six tree species ($P > 0.05$). From the 6 to 12th month, all the six tree species had remarkable growth, among which *Es* and *Ea* had relatively higher values of both inner and outer root biomass (Es_{inner}: 431.54 g m^{-2}; Es_{outer}: 399.72 g m^{-2}; Ea_{inner}: 465.89 g m^{-2}; Ea_{outer}: 365.54 g m^{-2}), of which their outer root biomass was significantly greater than other tree species ($P < 0.05$). From the 12 to 18th month, no significant difference was found between the root biomass of the six tree species and *Sl* was the only tree species that obtained positive growth for both the inner and outer roots (Sl_{inner}: 349.16 g m^{-2}, Sl_{outer}: 189.56 g m^{-2}), while the other five tree species had various patterns of biomass variation. To be specific, *Cc* increased its inner foot biomass from 298.40 g m^{-2} to 329.14 g m^{-2} whereas its outer root biomass decreased from 244.52 to 189.13 g m^{-2}. A decline of root biomass was observed for the other four tree species, among which *Ir*, *Ss*, and *Es* showed scarce inclination that both the inner and outer root biomass reduced accordingly. On the contrary, *Ea* remained the highest value of inner root biomass of 459.15 g m^{-2} but had an enormous biomass loss for its outer roots from 365.54 to 226.44 g m^{-2}.

Evolved patterns of root:shoot ratios

Based on each leaf's dry weight and area, the data of weighted mean *SLA* is given in Table 2. Combined with *PCA* and *LAI*, leaf biomass in the 6, 12, and 18th month was calculated as well. With *PCA* increasing from the 6 to 18th month as well as *LAI*, the calculated leaf biomass of all the six tree species exhibited a stable rising tendency, e.g., *Sl*: 69.62 g in the 6th month, 148.27 g in the 12th month, and 254.65 g in the 18th month. Associated with fine root biomass, the evolved root:shoot ratios were shown in Figure 6. In the 6th month, the six tree species had relative limited proportions of root biomass that their root:shoot ratios stayed between 0.01 and 0.20 (*Sl*: 0.11; *Ir*: 0.17; *Ss*: 0.15; *Cc*: 0.04; *Es*: 0.08; *Ea*: 0.08). Under the

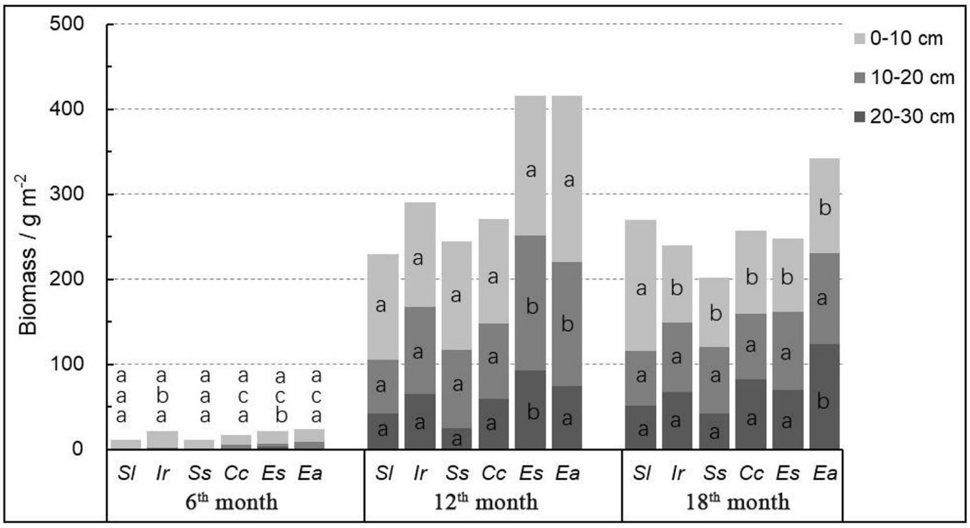

FIGURE 4
Vertical development of fine root biomass (g m^{-2}) of all the six tree species from the 6 to 18th month since plantation. The abbreviations of *Sl*, *Ir*, *Ss*, *Cc*, *Es*, and *Ea* were short for *Sterculia lanceolata*, *Ilex rotunda*, *Schima superba*, *Cinnamomum camphora*, *Elaeocarpus sylvestris*, and *Elaeocarpus apiculatus*. The light gray, medium gray, and black bars represent the fine roots in the soil layer of 0–10 cm (shallow layer), 10–20 cm (middle layer), and 20–30 cm (deep layer), respectively. The letters "a", "b", and "c" indicate significant differences ($P < 0.05$) between fine root biomass of different tree species in the same month.

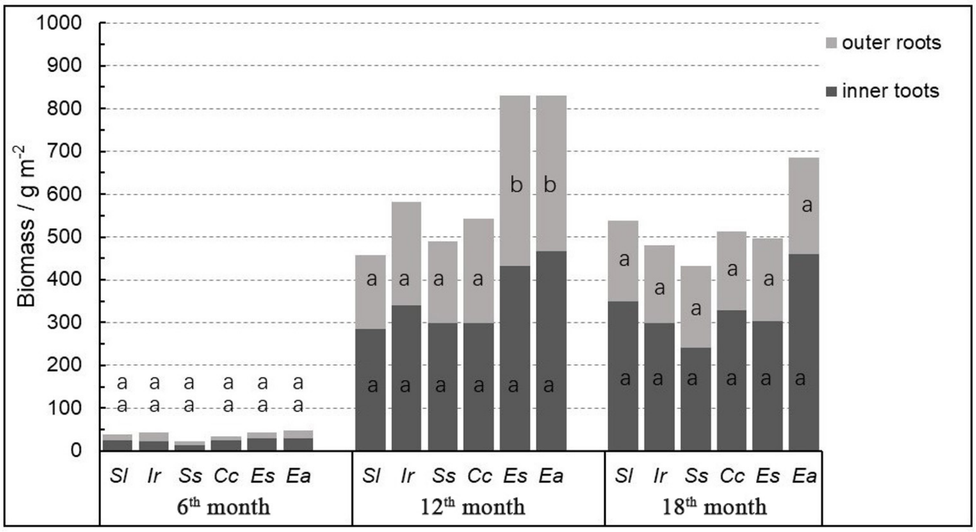

FIGURE 5
Horizontal development of fine root biomass (g m^{-2}) of all the six tree species from the 6 to 18th month since plantation. The abbreviations of *Sl*, *Ir*, *Ss*, *Cc*, *Es*, and *Ea* were short for *Sterculia lanceolata*, *Ilex rotunda*, *Schima superba*, *Cinnamomum camphora*, *Elaeocarpus sylvestris*, and *Elaeocarpus apiculatus*. The dark gray and light gray bars represent the inner roots (located at 15 cm to tree trunks) and outer roots (located at 30 cm to tree trunks), respectively. The letters "a" and "b" indicate significant differences ($P < 0.05$) between fine root biomass of different tree species in the same month.

tremendous development of the fine root biomass of all the tree species from the 6 to 12th month, their root:shoot ratios presented a conspicuous growth that they reached the peak in the 12th month (*Sl*: 0.59; *Ir*: 0.93; *Ss*: 0.97; *Cc*: 0.38; *Es*: 0.52; *Ea*: 0.43). From the 12 to 18th month, leaf biomass increment with synchronous decrement of root biomass resulted in various falls of root:shoot ratios (*Sl*: 0.40; *Ir*: 0.41; *Ss*: 0.33; *Cc*: 0.22; *Es*: 0.13; *Ea*: 0.17).

TABLE 2 Averaged dry weight (g) and leaf areas (m^2) of single leaf together with *SLA*, *PCA*, *LAI*, and leaf biomass with standard deviations of all the six tree species in the 6, 12, and 18th month since plantation.

Tree species	Dry weight (g ± SD)	Leaf area (m^2 ± SD)	SLA (m^2 g^{-1} ± SD)	*PCA* (m^2 ± SD)			*LAI* (m^2 m^{-2} ± SD)			Leaf biomass (g ± SD)		
				6th month	12th month	18th month	6th month	12th month	18th month	6th month	12th month	18th month
Sl	0.20 ± 0.02	0.0033 ± 0.0002	0.0164 ± 0.0004	1.13 ± 0.16^{a}	2.01 ± 0.28^{a}	3.14 ± 0.41^{a}	1.01 ± 0.07^{a}	1.21 ± 0.16^{a}	1.33 ± 0.18^{a}	69.62 ± 12.13^{a}	148.27 ± 29.21^{a}	254.65 ± 41.98^{a}
Ir	0.10 ± 0.01	0.0013 ± 0.0001	0.0128 ± 0.0004	0.50 ± 0.10^{b}	0.95 ± 0.21^{b}	1.54 ± 0.33^{b}	1.23 ± 0.13^{a}	1.62 ± 0.16^{a}	1.83 ± 0.26^{a}	48.28 ± 10.99^{a}	120.22 ± 26.77^{a}	219.97 ± 48.32^{a}
Ss	0.23 ± 0.01	0.0022 ± 0.0001	0.0093 ± 0.0001	0.28 ± 0.06^{c}	0.78 ± 0.19^{b}	1.54 ± 0.37^{b}	0.95 ± 0.05^{a}	1.14 ± 0.09^{a}	1.50 ± 0.13^{a}	28.87 ± 6.58^{b}	96.23 ± 22.14^{b}	248.16 ± 61.21^{a}
Cc	0.14 ± 0.01	0.0016 ± 0.0001	0.0112 ± 0.0001	1.54 ± 0.29^{a}	2.27 ± 0.46^{a}	3.14 ± 0.77^{a}	1.11 ± 0.08^{a}	1.35 ± 0.14^{a}	1.58 ± 0.17^{a}	152.49 ± 35.48^{c}	273.45 ± 61.14^{c}	442.96 ± 94.26^{b}
Es	0.12 ± 0.01	0.0011 ± 0.0001	0.0099 ± 0.0001	0.79 ± 0.16^{b}	2.01 ± 0.55^{a}	3.80 ± 0.92^{a}	1.22 ± 0.10^{a}	1.51 ± 0.16^{a}	1.83 ± 0.24^{a}	96.74 ± 29.74^{a}	306.51 ± 62.85^{c}	702.31 ± 150.56^{c}
Ea	0.66 ± 0.03	0.0072 ± 0.0004	0.0108 ± 0.0003	1.54 ± 0.25^{d}	3.14 ± 0.66^{c}	5.31 ± 0.84^{c}	0.99 ± 0.04^{a}	1.25 ± 0.11^{a}	1.53 ± 0.16^{a}	141.04 ± 35.68^{c}	363.43 ± 88.77^{d}	751.77 ± 184.21^{c}

The abbreviations of Sl, Ir, Ss, Cc, Es, and Ea were short for Sterculia lanceolata, Ilex rotunda, Schima superba, Cinnamomum camphora, Elaeocarpus sylvestris, and Elaeocarpus apiculatus. SLA, PCA, and LAI were short for specific leaf area, projected crown area, and leaf area index and these abbreviations were used hereinafter.
The letters a-d indicate significant differences ($P < 0.05$) between values of different tree species in the same month.

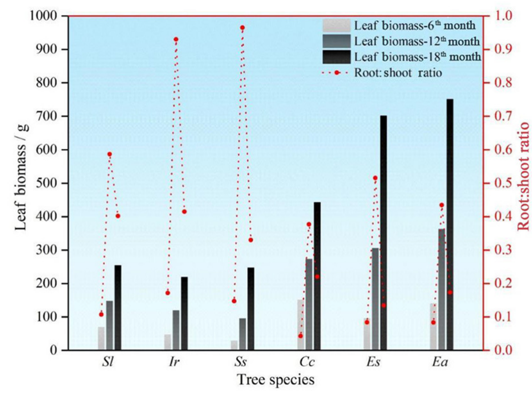

FIGURE 6
Leaf biomass (g) and root:shoot ratios of all the six tree species in the 6, 12, and 18th month since plantation. The abbreviations of *Sl*, *Ir*, *Ss*, *Cc*, *Es*, and *Ea* were short for *Sterculia lanceolata*, *Ilex rotunda*, *Schima superba*, *Cinnamomum camphora*, *Elaeocarpus sylvestris*, and *Elaeocarpus apiculatus*. The light gray, medium gray, and black bars represent the leaf biomass that follow the left *Y*-axis and the red dotted-line representing the development of root:shoot ratios match the right red *Y*-aixs.

Improvement of soil physical and chemical properties

Five physical and eight chemical variables were measured to analyze the soil revolution under the ecological remediation (Table 3). For physical properties, no significant difference was detected between June 2018 and December 2019, among which *Stp*, *Scp*, and *Sncp* presented minor increase (*Stp*: from 39.80 to 45.72%; *Scp*: from 35.66 to 39.31%; *Sncp*: from 4.14% to 6.41%) whereas *SMC* and *BD* exhibited slight decreases (*SMC*: from 22.64 to 19.90%; *BD*: from 1.28 to 1.23 g cm^{-3}).

In terms of chemical properties, except for *TN* (from 1.02 to 1.01 g kg^{-1}), the other variables displayed distinct development, especially for *AN*, *AK*, *SOM* showing significant increase (*AN*: from 47.78 to 152.60 mg kg^{-1}; *AK*: from 18.18 to 85.80 mg kg^{-1}; *SOM*: from 10.36 to 18.44 g kg^{-1}). Furthermore, soil acidity reduced with *pH* values rising from 4.20 to 5.04.

Discussion

Above-ground growth under typhoon disturbances from dialectical perspectives

Tree's growth is tightly relevant to its multiple ecosystem services (Moser et al., 2015; Rötzer et al., 2019). Generally, trees tend to provide multiple ecosystem services with towering heights, denser diameters, and luxuriant foliage (Gonzalez-Benecke et al., 2014; Escobedo et al., 2015). Taking typhoon's

TABLE 3 Measured soil physical properties including soil moisture content (*SMC*, %), soil total porosity (*Stp*, %), soil capillary porosity (*Scp*, %), soil non-capillary porosity (*Sncp*, %), bulk density (*BD*, g cm^{-3}), and chemical properties including *pH* values, soil organic matter (*SOM*, g kg^{-1}), total nitrogen (*TN*, g kg^{-1}), total phosphorus (*TP*, g kg^{-1}), total potassium (*TK*, g kg^{-1}), available nitrogen (*AN*, mg kg^{-1}), available phosphorus (*AP*, mg kg^{-1}), available potassium (*AK*, mg kg^{-1}).

Soil properties		*n*	Date	
			June 2018	December 2019
Physical properties	*SMC* (%)	5	22.64 ± 1.90^a	19.90 ± 2.82^a
	Stp (%)	5	39.80 ± 2.66^a	45.72 ± 9.14^a
	Scp (%)	5	35.66 ± 2.86^a	39.31 ± 4.77^a
	Sncp (%)	5	4.14 ± 1.65^a	6.41 ± 1.34^a
	BD (g cm^{-3})	5	1.28 ± 0.06^a	1.23 ± 0.06^a
Chemical properties	*TN* (g kg^{-1})	5	1.02 ± 0.25^a	1.01 ± 0.23^a
	TP (g kg^{-1})	5	0.26 ± 0.10^a	0.31 ± 0.14^a
	TK (g kg^{-1})	5	15.40 ± 4.78^a	21.52 ± 6.89^a
	AN (mg kg^{-1})	5	47.78 ± 16.91^a	152.60 ± 21.05^b
	AP (mg kg^{-1})	5	1.08 ± 0.19^a	1.09 ± 0.17^a
	AK (mg kg^{-1})	5	18.18 ± 9.56^a	85.80 ± 27.62^b
	pH	5	4.20 ± 0.04^a	5.04 ± 0.74^a
	SOM (g kg^{-1})	5	10.36 ± 3.32^a	18.44 ± 3.67^b

The letters "a" and "b" indicate significant differences ($P < 0.05$) between the values in June 2018 and December 2019.

enormous influences and following fragile soil environment into consideration, however, it is challenging to make simple encouragements for trees' above-ground growth. This is because although dominant above-ground growth implies trees' well adaption and potential ecosystem services to some extent, their greater above-ground profiles will increase their windward areas and consequently expose the whole tree to higher probabilities of lodging. To be specific from morphological perspectives, trees with larger sizes of heights and crowns but thinner diameters may suffer more from wind smashes, which is more likely to be bent or broken off under typhoon circumstances.

In this research, *Cc* exhibited advantages in ground diameter but relatively small size of crown and height. Compared to its restricted growth of diameters and heights under drought stress (Hu et al., 2015), it could be inferred that *Cc* invested more on stem diameter growth under typhoon disturbances rather than crown and height, which might lead to well adaptions to strong breeze. For *Sl*, *Ir*, *Ss*, and *Ea*, their accordant growth of ground diameter, height, and crown area reflected an average-allocated above-ground process, showing an common wind-adaption capacity. On the contrary, *Es* had the most robust growth of height accompanying with second largest crown area and medium ground diameter, which was consistent with some previous studies (Li, 2019). Such type of tree profile was disadvantageous for being planted in typhoon-disturb areas from morphological perspectives, which might led to comparatively difficult maintenance of stabilities under circumstances of strong breeze.

Importance of root growth and root:shoot ratios in coping with wind damage

Fine root growth, playing a crucial role in providing multiple ecosystem services by absorption of water and nutrients, reflected tree's adaption to the plantation areas and improvement of soil qualities adequately (Jackson et al., 2008; Fornara et al., 2009; Fortier et al., 2019; Cusack and Turner, 2021). Our research explored the growth of root biomass of all the surveyed tree species since they were planted, based on which specific patterns were clarified in the horizontal and vertical levels.

The six tree species' specific patterns of fine root development as well as dynamic root:shoot ratios provided profound insights how well they acclimated to the below-ground environment. For *Sl*, it exhibited distinct overall fine root biomass growth within the whole 18 months, implying a steady below-ground investment that could guarantee water and nutrients uptake (Guan et al., 2014; Farneselli et al., 2015). Furthermore, its thriving deep and outer roots proved improved turnover processes ulteriorly and contributed to establishing stable below-ground architectures (Zhang et al., 2020). To be concluded, *Sl*'s fine root development presented distinguished advantages in environmental adaption and morphological stability. The fine root biomass of the other five tree species increased from the 0 to 12th month but decreased from the 12 to 18th month, revealing dynamic adjustment of below-ground processes. Moreover, their reduction of root biomass occurred from different parts of roots, implying various strategies under typhoon-effect areas. To be detailed from the vertical perspective, all the three layers of *Es*'s root biomass showed consistent decrement. In contrast, root biomass in the shallow and middle layers of *Ir*, *Ss*, *Cc*, and *Ea* declined while their root biomass in the deep layers raised from the 12 to 18th month, which had drawn our further attention. Previous researches indicated that deep roots could be of pivotal importance to alleviate survival stresses, particularly played a central role for some plants in tropical and subtropical environments (Gewin, 2010; Pierret et al., 2016). In addition, some researchers proposed that trees expended less energy on constructing shallow roots rather than deep roots in general, however, they might make enhanced investments on deep roots in coping with environmental challenges such as drought, floods, and soil degradation (Schenk and Jackson, 2005; Schenk, 2008). Hence, the development of deep roots could lead *Ir*, *Ss*, *Cc*, and *Ea* to a better acclimation than *Es* to the infertile soil environment disturbed by typhoon events. In respect of horizontal root growth which was compactly relevant to tree's stabilization, two types of tendencies were observed for the five tree species. The inner and outer root biomass of *Ir*, *Ss*, and *Es* decreased simultaneously, while *Cc* and *Ea* maintained their inner root development at the expense of the decline of outer root biomass. From morphological perspectives, trees with widely and averagely distributed roots would achieve more stability rather than those with centralized roots (Leuschner et al., 2004). Therefore, the prior loss of outer root biomass might weaken *Cc*'s and *Ea*'s capacities of dealing with strong wind disturbances.

Root:shoot ratio was widely used to estimate relative biomass allocation between roots and shoots (Ledo et al., 2018; Maškov and Herben, 2018). Besides, this ratio helped to reveal how plants confronted various short- or long-term stresses, which effectively promoted to a better understanding of how well the plants would adapt to the local environment in the future (Sainju et al., 2017; Krell et al., 2018). Although it was better to calculate the overall biomass of below- and above-ground parts, in this study we calculated the ratio of fine root biomass to leaf biomass instead since all the surveyed trees were strictly protected and prohibited from harvest. This kind of root:shoot ratio could not be completely same as the common root:shoot ratio, however, it could remain to provide information for researchers to partly know the relationship between above- and below-ground biomass (Zhang et al., 2019). The root:shoot ratios of all the six tree species showed a trend of rising-descending within the whole observation period, reaching peaks in the 12th month. This indicated that they had higher percentages of below-ground investment within the first year since they were planted, and after which they adjusted the inclinations to above-ground development. According to other researches under stresses (Benjamin et al., 2014; Agathokleous et al., 2019; Zhang et al., 2020), plants might give more priorities to root development to guarantee their absorption of water and nutrients rather than stems or branches. This was because the fragmented soil environment was generally lack of fertilities and moisture, making root constructions being expedited to be deeper and more expansive. Accordingly, the above-ground process could be slowed down and achieved less investment due to its non-urgency. Nonetheless, this trend would not be maintained invariably as photosynthesis remained to be key importance for tree's survival that subsequent compensatory support was given to above-ground growth (Ågren and Ingestad, 1987; Chaves et al., 2002), resulting in a resilient balance between roots and shoots. In our research, the six tree species reduced root:shoot ratios together with increased leaf biomass from the 12 to 18th month, implying accelerations of above-ground processes. On the positive premise of this above-ground growth, specific attentions remained to be paid to avoid or reduce top-heavy phenomena. For instance, in the 18th month, the root:shoot ratios of *Es* and *Ea* were obviously lower than other tree species, though not meant failure of root growth, the larger proportion of above-ground biomass increased trees' vulnerabilities to strong winds' disturbances and actions should be adopted to alleviate the possibilities of lodging or breaking off.

Impact of ecological remediation on soil physical and chemical properties

Through root turnover, litter deposition, and interactions with microorganism, vegetation could reform soil properties and recover fertilities consequently (Barrios et al., 2005; Yavitt et al., 2011; Högberg et al., 2017). For typhoon-affected areas, the restoration of soil qualities played a fundamental role in re-establishment of habitat, maintaining biodiversity, and facilitating ecological balance (Hou et al., 2019; Abbas et al., 2020). Measured in June 2017 and December 2018, the soil physical and chemical properties were evaluated for the efficiency of the ecological remediation. Concerning the physical properties, though no significant difference was detected between June 2018 and December 2019, the increase in *Stp* revealed that the availability and movement of air or water were facilitated in the soil environment (Mishra et al., 2003; Ramesh et al., 2019). In addition, the rise of *Scp*, reflecting water in soil pores resisting the forces of gravity, indicated that root turnovers had preliminarily improved soil's structure by retaining more moisture for trees' growth (Tangyuan et al., 2009; Or et al., 2013; Wang and Shao, 2013). In terms of chemical properties, all the variables showed escalation to different extent, eminently for the upsurge of *AN*, *AK*, and *SOM* ($P < 0.05$). Considering the below-ground development of all the surveyed tree species, the root growth might be the essential role that participated actively in soil chemical evolution and promoted the release of microelement (Jia et al., 2008; Postma and Lynch, 2011). Among all the chemical measured variables, the slight changes of *TP* and *AP* could be resulted from the inactive nature of phosphorus, especially in acidic conditions (Li et al., 1995). In conclusion, trees planted for the ecological remediation had leaded to the soil environment's positive evolvement, primarily on the chemical properties rather than physical ones.

Selection of appropriate tree species for ecological remediation against typhoon disturbances

With the demand for ecological remediation increasing globally, efficiency and effectiveness became principal requirements against various environmental challenges (Burton, 2014; Camarretta et al., 2020). For forest restoration after typhoon events, the degraded soil environment raised the requirement of trees' acclimation. Moreover, as regarded as pioneer tree species, how well they improved environment conditions including soil physical and chemical properties determined the efficiency of subsequent plantation of other tree species (Tabarelli et al., 2010; Parraga-Aguado et al., 2014). Therefore, the preferred selection should be given to those tree species with robust physiological growth, particularly with steady and strong root development. To be detailed, the vigorous root development led to an enhanced capacity of absorption of water and nutrients while the intensified above-ground process adequately disclosed photosynthesis, respiration, and relative ecosystem services (Kreuzwieser and Gessler, 2010; Weemstra et al., 2016; Maia et al., 2020; Rötzer et al., 2021). From our research, tree species like *Sl* and *Cc* displayed advantages in root growth in overall, horizontal, and vertical levels, which could be positive for their effectiveness in the ecological remediation. On the contrary, with great fluctuations of root biomass within the growing period and tendencies of maintaining shallow and centralized roots, it could be worried for *Es*'s performance in its environmental acclimation under the future windy circumstances.

Apart from tree species' basic growths, whether and how well they would cope with typhoon disturbances in the future had drawn our attention for further analysis. In this research, root:shoot ratios, representing strategies and tolerances under multiple disturbances (Barton and Montagu, 2006; Lynch et al., 2012), were applied to evaluate the potential resistance of the six surveyed tree species against strong winds. Based on some previous findings, those adaptive trees tended to increase the below-ground proportions facing drier or harsher environmental conditions (Tahere et al., 2000; Zhang et al., 2020). From our measurement, root:shoot ratios of *Sl*, *Ir*, and *Ss* were consistently higher than other tree species within the whole observation period. In addition, the sharp increase of root:shoot ratios of them occurred in their juvenile stage, during which the trees were still very young. Precisely because of it, the high values of root:shoot ratios implied greater masses of below-ground than above-ground parts, which reflected more stable tree profiles. On the contrary, the dynamic patterns of root:shoot ratios of *Cc*, *Es*, and *Ea* showed no advantages of biomass allocation for below-ground development, even in the first year since plantation. Another worthy phenomenon was that all the tree species reduced their root:shoot ratios from the 12 to 18th month, probably due to the robust development of above-ground parts such as crowns. Therefore, concerning the probable coming of new typhoon events, special care such as physical supports could be adopted to enhance trees' stability.

To sum up, tree species selected for ecological remediation should be profoundly evaluated for their competence and suitability. The appropriate tree species planted in typhoon-affected areas should acclimated to windy environment well. Firstly, it is crucial for them to have robust growth, particularly the root development. Furthermore, the capacity of improving soil qualities assured a favorable environment for subsequent plantations. It could also be advisable to select those tree species with inherent advantages, such as high values of root:shoot ratios revealing relatively steadier tree profiles from morphological perspectives.

Conclusion

Typhoon Hato (2017) intruded in Zhuhai city and had severe impact on the local forest ecosystem, for which the local administrative department launched ecological remediation via plantation of various tree species. In this research, we selected six planted tree species as the objects and measured their tree growth and influences on the soil qualities, aiming to analyze their environmental adaption and the efficiency of the ecological remediation.

Our results showed that the six surveyed tree species had different above- and below-ground growth patterns. With robust root development in both horizontal and vertical levels combined with relatively short and thick above-ground profile, *Sl* and *Cc* were likely to cope well with typhoon disturbances. Tree development of *Ir* and *Ss* led to moderate acclimation to windy environment, while *Es* and *Ea* were not recommended to be planted under typhoon-effect areas concerning their unstable root development. In addition, the ecological remediation did improve the soil properties, specifically for the chemical characteristics including *AN*, *AK*, *SOM*.

The preliminary growth of the planted tree species and improved soil qualities proved the efficiency of the ecological remediation. To achieve further effect in the future, it was better to choose those tree species with vigorous root development together with steady and high values of root:shoot ratios, which might be advantageous for coping with typhoon disturbances. The tree species with prosperous above-ground growth were not suitable for areas facing strong winds directly but could be planted in leeward regions to amplify their landscape functions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CZ and WQ designed the study, performed the research, analyzed data, and wrote the paper. LS analyzed the data. QZ managed the project. All authors contributed to the article and approved the submitted version.

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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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