How to Accurately Detect and Assess the Street Trees Risk in Mega Cities: A Tree Risk Assessment Method and Its Application

Kun He
Shanghai Institute of Technology
Longlong Wei
Shanghai Institute of Technology
Nan Li
Shanghai Institute of Technology
Junjie Wang
Shanghai Institute of Technology
Sihao Ye
Shanghai Institute of Technology
Benyao Wang (wangbenyao@163.com)
Shanghai Municipal Landscape Management and Instructional Station

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Abstract

Traditional visual tree assessment based on rapid diagnosis is suitable for the rapid, large-scale assessment of urban tree risks, but it cannot accurately determine internal decay in trunks and underground root systems, may leading to highly subjective evaluation results. A risk matrix-based street tree risk assessment system was established by combining a visual tree assessment method, nondestructive detection techniques, information acquisition, and data analysis using a geographic information system (GIS). The method was used to conduct risk detection and assessment on 1,001 street trees with a diameter at breast height greater than 40 cm on 14 streets in a Historic Features Protection Area of Shanghai. The result showed that: 1) The branch and the trunk risk possibility of the vast majority of street trees were at level 2 or below, while the root risk possibility of more than one third of the trees was at level 3 or above. 2) The risk level of 23% of the trees in the protected area was moderate or above, while that of most of the other trees was at a negligible or acceptable level. The risk consequence severity level was high for trees on Tianping Road but low for trees on Donghu Road and Taojiang Road. 3) The street tree risk level shows a strong correlation with the presence of tree cavities, diseases and insect pests, the depth and range of root distribution, leaning, and internal decay in trunks, and the risk points are concentrated in the trunk and root system. Conducting a risk assessment of street trees based on precision diagnosis techniques can improve the scientific rigor of the assessment. The results of this work can provide a basis for the accurate assessment of street trees risk in some large cities, which provides a new assessment system for the trees risk assessment in important urban areas, and the approach is conducive to the refined management of urban greening trees.

Introduction

Street trees are an important component of urban greening, and they provide many positive benefits to the urban environment and the wellbeing of residents (Mullaney et al., 2015; Kardan et al., 2015; Nowak et al., 2006; Sreetheran et al., 2011; Roy et al., 2012; Lopes et al., 2009). Under various natural and anthropogenic stresses, such as complex urban environments (Jia et al., 2021a; Jim, 2003; Burton, 2002), high-density building layouts (Tan et al., 2016; Wong, 2010), and poor growth conditions (Jim and Zhang, 2013; Jim, 2003; Loeb, 1992; Haaften et al., 2021), street trees are prone to unhealthy conditions, such as large crown deviation, leaning, internal decay, and root damage (Meunpong et al., 2019; Jia, 2014; Shu et al., 2011; Gao and Liu, 2014).. Severe weather events such as strong winds and heavy rain can trigger various risks, such as the breaking and falling of branches, trunks, or the entire tree (Gao and Liu, 2014), posing serious threats to urban traffic and the safety of residents and their property (Jia et al., 2021a; Lazim and Misni, 2016; Lopes et al., 2009). By performing tree risk assessment to identify street tree risk hazards early and adopting timely targeted management measures to eliminate or mitigate tree risks, cities can prevent and control street tree-related safety hazards.

Commonly used tree risk assessment and management systems include the International Society of Arboriculture (ISA) Tree Hazard Evaluation (Matheny and Clark, 1994), the United States Department of Agriculture Forest Services Community Tree Risk Evaluation Method (Pokorny, 2003), and the ISA Tree Risk Assessment Best Management Practice (BMP) Method (Smiley and Lilly, 2017). These methods are similar in many ways and mainly include evaluations of the tree structure, defects, and potential hazards, but they differ in how they weight each underlying risk factor(Norris, 2007; Matheny and Clark, 2009). For visual tree assessment (VTA), the method proposed by Mattheck et al is currently used in most cities in China (Gao and Liu, 2014; Klein et al., 2020; Dare et al., 2015; Cai, 2014; Wang et al., 2017). However, although this fast diagnosis method is based on visualization and simple tools, it cannot quantitatively evaluate certain indicators, leading to highly subjective evaluation results, making it impossible to accurately determine internal decay in trunks and underground root systems. While this method is suitable for the rapid, large-scale assessment of urban tree risks (He et al., 2021; Li et al., 2009), more accurate diagnosis and evaluation methods are needed for ancient or large trees (Jim, 2005; Júnior et al., 2019; Hu et al., 2000; Koeser et al., 2017; Ma et al., 2017; Dare et al., 2015)

In this study, street trees in the Hengshan Road–East Fuxing Road Historical Features Protection Area in Shanghai were subjected to risk detection through a precise diagnosis technique that combines VTA and nondestructive detection methods, including the PICUS-3 Sonic Tomography Technology and Ground-Penetrating Radar technology. In addition, a comprehensive assessment system was constructed based on the risk matrix method to carry out street tree risk assessment and risk level classification as well as to analyze the spatial distribution and main risk points of the trees in the study area. The purpose of the study is to provide technical references for the risk assessment and management of street trees in mega cities.

Study Area And Methods

Study area and subjects

Shanghai is located in East China, with a subtropical monsoon climate and four distinct seasons. More than 60% of the rainfall in Shanghai is concentrated between May and September, and it is affected by typhoons mainly during the period from July to September. Downtown areas of Shanghai are densely populated, with high-rise buildings and a limited amount of urban green space. Rapid urban development has exerted tremendous pressure on urban trees.

The Hengshan Road–East Fuxing Road Historical Features Protection Area, the largest protected area of historical and cultural features in Shanghai, is the birthplace of the city and its urban hub. Street trees in this area are an important component of the historical and cultural protection strategy. In this study, from the autumn of 2020 to the spring of 2021, we investigated 1,001 street trees with a diameter at breast height greater than 40 cm on 14 main roads in the Hengshan Road-East Fuxing Road Historical Features Protection Area to conduct an accurate risk evaluation and assessment (Fig. 1). The street trees were mainly *Platanus orientalis* Linn, *Pterocarya stenoptera* (C. DC), *Sophora japonica* Linn., *Quercus acutissima* Carruth and *Sapium sebiferum* (L.) Roxb. *Platanus orientalis* is the most abundant tree species, with a total of 884 individuals that account for 88.31% of all street trees, and *Pterocarya stenoptera* is the second most abundant tree species, with a total of 109 individuals that account for 10.89% of all street trees.

Methods

Tree risk evaluation method

The VTA evaluation method was combined with two nondestructive detection techniques, including the PICUS-3 Sonic Tomography Technology and Ground-Penetrating Radar technology, to perform an accurate assessment and comprehensively diagnose the overall risk status of the street trees.

1. Sample data from the survey site were acquired, and then distribution point data were exported to ArcGIS 10.8 software for processing, analyzing and generating graphs. Various indicators, including tree species,

coordinates, tree height, DBH, crown width, tilt, and tree potential, were used.

2. Based on the preliminary survey results, street trees with DBH of greater than 40 cm were selected for VTA assessment. The assessment includes branch, trunk, root system and its surrounding environment. In reference to previous research results (He et al., 2021) and recommendations of ISA, the following main risk points were selected for detection. Among them, the branches part mainly include large crown deviation, large dead branches, the presence of fungal fruit bodies, diseases and insect pests, dieback in the upper portion; The truck part mainly include leaning of trees, tree cavities, mechanical damage; The root system part mainly include packing roots, belowground pipe gallery construction; The surrounding environment include possible falling site, road grade, and density of surrounding buildings.
3. The presence of internal decay and the distribution of decay in the trunks and roots of street trees were detected using the Picus-3 Sonic Tomography Technology and the GPR technology. Picus-3 stress wave is mainly used to detect the internal cavity and decay of different tree trunk. The detection is mainly divided into three sections with different heights, which are 30cm, 160cm and 210cm respectively (Fig. 2). The root distribution was detected in the vertical and horizontal directions; the vertical distribution of roots was divided into three zones, i.e., 0–20 cm, 21–40 cm, and 41–100 cm from the ground surface, while the horizontal distribution was investigated using the concentric circle method (with the trunk of the tree as the center of the circle). Due to limitations in the operating conditions, only three semicircular cross-sections on the sidewalk side and two semicircular cross-sections on the roadway side were scanned. The plane radii of these cross-sections were 1.0 m, 1.5 m, and 2.0 m, respectively (Fig. 2).

Tree risk assessment method

1)Risk Matrix

The tree risk assessment index system has built based on the risk matrix method which is an evaluation method combining qualitative analysis and quantitative analysis. The risk matrix can comprehensively evaluate and grade the tree risk consequence severity and risk occurrence possibility. Tables 1–4 are the grade quantification table of each element in the risk assessment process of street tree.

Table 1
street tree risk possibility level

Possibility level(P)	Grade	Description of the risk occurrence possibility
□(4)	IV (4/ Extremely high)	Highly likely, risks are very easy to happen in the near future
□(3)	III (3/ high)	High possibility, risks are easy to occur due to their poor growth.
□(2)	II(2/medium)	Medium probability, the occurrence of risks are reasonably predictable
□(1)	I (1/Low)	Low possibility, risks can occur if the weather is bad

Table 2
Street tree risk consequence severity level

Consequence severity level (S)	Grade	Description of the consequences of the risk
□(4)	4/Extreme	Tree risk will pose a serious threat to human life and public property, and can cause major accidents
□(3)	3/Serious	Serious injury to people, vehicles, buildings, etc
□(2)	2/Mild	Minor injuries to people, vehicles, buildings, etc
□(1)	1/Negligible	Almost no harm

Table 3
Risk value comparison table

Possibility	Consequence severity level			
	□(1/Negligible)	□(2/Mild)	□(3/Serious)	□(4/Extreme)
□(1/Low)	1	2	3	4
□(2/medium)	2	4	6	8
□(3/ high)	3	6	9	12
□(4/ Extremely high)	4	8	12	16

Table 4
Risk level comparison

Risk level R	Interpretative statement
IV (12–16)	Significant risk (This risk factor is very unsafe and will cause serious consequences)
III (8–9)	Medium risk (This risk factor is unsafe and it is very likely that trees will collapse or break, so measures should be taken immediately to control This risk factor)
II (3–6)	Acceptable risk (This risk factor is relatively safe, but there are potential risks, which should receive attention)
I (< 3)	Negligible risk (This risk factor is basically safe, but it does not rule out that there are certain potential safety hazards, so This risk factor should continue to be monitored)
Description:	
1 Risk value = street tree risk level possibility × street tree risk consequence severity.	
2. See Table 4 for the risk classification criteria in the risk matrix.	

2) Construction of the evaluation index system

Studies have shown that common tree risks include tree collapse due to root rot and trunk and branch breakage due to trunk and branch decay (Roson-Szeryńska et al., 2014), which can damage vehicles and buildings and harm pedestrians (Lazim and Misni, 2016). The evaluation items and indicators used in this study were selected based on the latest relevant technical systems, the results of previous studies(Dunster et al., 2017; He et al., 2021), and precision evaluation techniques. The evaluation items included three parts: branches, trunks, and roots. The evaluation indicators of the comprehensive visual evaluation method along with newly added indicators, such as the internal decay in trunks and the depth and range of root distribution, were used. Based on these indicators, an accurate street tree risk assessment index system that includes the risk occurrence possibility (P) and the risk consequence severity (S) was established (Table 5).

Table 5
Street tree risk assessment index system and scoring standard

Risk assessment A	Evaluation item B	Evaluation index C		Index scoring standard			
Risk possibility P	Branch B1	Profoundly lopsided canopy C1		0 (none)	1 (mild)	2 (moderate)	3 (severe)
		Large dead branch C2		0 (none)	1 (mild)	2 (moderate)	3 (severe)
		Fungal fruiting bodies C3		0 (none)	1 (mild)	2 (moderate)	3 (severe)
		Pests and diseases C4		1 (a few small branches or none); 2 (a few intermediate branches); 3 (large branches or many intermediate branches); 4 (one main branch or more than one large branch); 5 (more than one main branch)			
		Dieback C5		0 (none); 1 (≤ 25%); 2 (≤ 50%); 3 (≤ 75%); 4 (> 75%)			
	Trunk B2	Tree leaning C6		1 (≤ 10°); 2 (≤ 20°); 3 (≤ 30°); 4 (≤ 40°); 5 (> 40°)			
		Tree hole C7		0 (none); 1 (repaired, recovered); 2 (repaired, unrecovered); 3 (tend not to heal); 4 (rotted, hollow)			
		Mechanical damage C8		0 (none)	1 (mild)	2 (moderate)	3 (severe)
		Rot inside the tree/cavity C9	Section A	0. (None of the three cross-sections are rotted) 1. (All three cross-sections have rotted, all with an area proportion of ≤ 20%) 2. (At least one of the three cross-sections has rotted, with an area proportion of > 20%) 3. (At least one of the three cross-sections has rotted and has an area proportion of ≥ 50%, or one section has an area proportion of ≥ 30% and another has an area proportion of ≥ 20%) 4. (At least one cross-section has rotted and has an area proportion of > 70% or one section has an area proportion of > 50% and another section has an area proportion of ≥ 20%)			
			Section B				
			Section C				
	Root system B3	Distribution range C10		1 (mild)	2 (moderate)	3 (severe)	
			Proportion of area 1 (circles 1 and 4)	Healthy (30–44%)	Normal (25–29% or 45–50%)	Poor (< 25% or > 50%)	
			Proportion of area 2 (circles 1 and 2)	Healthy (50–60%)	Normal (40–49% or 61–70%)	Poor (< 40% or > 70%)	
		Distribution depth C11		1 (mild)	2 (moderate)	3 (severe)	

Risk assessment A	Evaluation item B	Evaluation index C	Index scoring standard			
		0–20	Healthy (6–11%)	Normal (3–5% or 12–15%)	Poor (< 3% or > 15%)	
		20–40	Healthy (34–45%)	Normal (27–33% or 46–52%)	Poor (< 27% or > 52%)	
		40–100	Healthy (44–60%)	Normal (33–43% or 61–70%)	Poor (< 33% or > 70%)	
		Rootbound C12	0 (none)	1 (mild)	2 (moderate)	3 (severe)
	Growth environment stress status B4	Underground pipeline construction C13	1 (yes)	2 (no)		
Risk consequence severity level S	Tree failure site B5	Possible breaking/falling part C14	1 (branch)	2 (trunk)	3 (whole plant)	
	Regional risk status B6	Road grade C15	1 (low)	2 (moderate)	3 (high)	
		Building density C16	1 (low)	2 (moderate)	3 (high)	4 (very high)

3) Risk matrix table and risk level determination

The street tree risk level was determined using the risk matrix method, in which the street tree risk consequence severity and possibility of risk occurrence were determined by combining the qualitative and quantitative analyses. The risk possibility (P) was mainly assessed based on the structural problems of a tree, and the pattern of tree failure was identified according to the indicators in the B1, B2, B3, and B4 categories to determine whether the tree was structurally damaged. The P value was assigned a value of 1 to 4 to represent low, moderate, high, and very high levels of risk, respectively. The risk consequence severity (S) was mainly determined by growth conflicts, and the scores of the indicators in the B5 and B6 categories were assigned to one of the following categories to obtain the S level category: I ($2 < S \leq 4$ points), II ($4 < S \leq 6$ points), III ($6 < S \leq 8$ points), and IV ($8 < S \leq 10$ points). The P and S values were quantified, and these values were substituted into the risk matrix table to obtain the street tree risk level (R) to improve the accuracy and reduce the subjectivity of the assessment (Table 4).

Data and statistical methods

The data were collated and analyzed using EXCEL software to obtain the main risk points of street trees in the protected area. The spatial distribution chart of street tree risks was generated after importing the data into ArcGIS for kernel density processing and analysis. The correlation between the street tree risk level and each of the indicators was analyzed using R 4.1.0, and the analysis results were then visualized.

Results

Accurate diagnosis of street tree risk

As shown in Fig. 3, the tree branch risk possibility (P) of more than 93% of the trees was at level II or below, while 5.99% and 0.60% of the trees had level III and level IV branch risk P values, respectively. Among the *P. orientalis* trees, 50 had level III branch risk P values, while three had level IV branch risk P values; among the *P. stenoptera* trees, nine had level III branch risk P values, and two had level IV branch risk P values; only one *S. sebiferum* tree had a level IV branch risk P value. Thus, the safety risk of these trees needs to be closely monitored.

The trunk risk possibility (P) of more than 85% of the street trees was at level II or below, while 12.59% and 1.80% of the trees had level III and level IV trunk risk P values, respectively (Fig. 3). Approximately 89% of the *P. orientalis* trees had level II or below trunk risk P values, while approximately 47% of the *P. stenoptera* trees had level III or above trunk risk P values. As revealed in the field survey, these values were due to various degrees of mechanical wounds or termite or fungal infestation that had not been promptly addressed.

The root system risk possibility (P) of more than 37% of the street trees was level III or higher (Fig. 3). The survey data showed that most of the street tree root systems were concentrated in the 0–50 cm depth range, the ratio of canopy to root system was seriously unbalanced, and the root systems of a considerable proportion of the street trees were at a high level of risk. Among the *P. orientalis* trees, 288 had level III root system risk P values, and 51 had level IV root system risk P values; among the *P. stenoptera* trees, 27 had level III root system risk P values, and three had level IV root system risk P values. The root system safety risk of these trees needs to be closely monitored.

Street tree risk assessment and analysis

Overall risk assessment of street trees

As shown in Fig. 4, more than 74% of the street trees showed a risk possibility (P) level of II or below, while most of the street trees showed risk consequence severity (S) levels of II and III, accounting for 25.17% and 63.14%, respectively, of all trees. More than 76% of the street trees showed a risk consequence (R) level of II or below, while 194 trees showed a risk consequence level R of III, and 42 trees showed a risk consequence (R) level of IV. These trees should be closely monitored, and appropriate management measures should be taken.

As shown in Fig. 5, among five street tree species, 78% of the *P. orientalis* trees showed a risk possibility level of II or below, indicating that the risk of *P. orientalis* trees in the protected area is moderate; more than 56% of the *P. stenoptera* trees showed a risk possibility level of III or above, indicating that the risk of *P. stenoptera* trees in the protected area is high; one *S. sebiferum* tree and one *S. japonica* tree showed a risk possibility level (P) of IV. For *P. orientalis* and *P. stenoptera*, 83% and 91% of falling/breaking parts were in the branches of *P. orientalis* and in the trunk of *P. stenoptera*, respectively.

Overall spatial pattern of street tree risk

As shown in Fig. 6, Dongping Road and Fenyang Road showed the highest average branch (B1) risk possibility level P values, while Baoqing Road and Taojiang Road showed the lowest risk possibility level P values (Fig. 6-a). The major causes of a high branch risk were severe disease and insect pests, and the minor causes were dieback in the upper portion and large crown deviation. Dongping Road and Wukang Road showed the highest average trunk (B2) risk possibility level P values, while Gao'an Road and Gaoyou Road showed the lowest average trunk (B2) risk possibility level P values (Fig. 6-b). The major cause of a high trunk (B2) risk possibility level P value was the presence of tree cavities and internal decay in trunks, and the minor cause was leaning of trees. Gao'an Road and Gaoyou Road showed the highest average root system (B3) risk possibility level P value, while Baoqing Road and Yueyang Road showed the lowest average root system (B3) risk possibility level P value (Fig. 6-c). The main cause of a high root system (B3) risk possibility level P was belowground pipe gallery construction, which damaged the root system on the motorway side and led to an uneven distribution of the range and depth of the root system.

As shown in Fig. 7, Dongping Road and Wukang Road showed the highest average overall risk possibility level P values, while Baoqing Road and Gaoan Road showed the lowest average overall risk possibility level P values (Fig. 7-a). Taiyuan Road and Tianping Road showed the highest risk consequence severity level S values, while Donghu Road and Taojiang Road showed the lowest risk consequence severity level S values (Fig. 7-b). Guangyuan Road and Tianping Road showed the highest average risk level R values, while Donghu Road and Taojiang Road showed the lowest average risk level R values (Fig. 7-c). Tianping Road showed the highest risk consequence severity level S and risk level R values, mainly due to the high road grade, high building density, recent damage to the root systems of street trees caused by the construction of an underground pipeline, branches with diseases and insect pests, and the presence of cavities and decay within tree trunks.

Street tree risk point analysis

The risk assessment point is the key factor in the risk possibility of street trees. As shown in Fig. 8, among the 1,001 street trees investigated, the risk factor root depth distribution (C11) was found in 873 trees, with a moderate risk severity; the risk factor root range distribution (C10) was found in 754 trees, with a moderate risk severity; and the risk factor belowground pipe gallery construction (C13) was found in 473 trees. The above three factors are the most common indicators of street tree risk, and they all involve the root system. The frequency of risk factors involving the trunks and branches (C1–C9) of the trees was lower than that of those involving the roots, and the risk factor internal decay in trunks (C9) was found in 468 trees, with a mild severity level; the risk factor tree cavities (C7) was found in 322 trees, mostly with a high severity level. Leaning (C6) and diseases and insect pests (C4) were also common. Other factors only had a limited influence on the risk possibility.

As shown in Fig. 9, the risk level of the street trees showed a significantly positive correlation with tree cavities (C7), diseases and insect pests (C4), the range of root distribution (C10), the depth of root distribution (C11), leaning of trees (C6), and internal decay in trunks (C9); all of these factors involve the trunks and roots of the trees. The risk level of the street trees showed a positive correlation with large crown deviation (C1), large dead branches (C2), and root packing(C12), but no significant correlation with fungal fruiting bodies (C3) was observed. The results of the correlation analysis indicate that there was a significant positive correlation between the presence of large dead branches (C2) and dieback in the upper portion (C5); the presence of fungal fruiting bodies (C3) was positively correlated with dieback in the upper portion (C5) and mechanical damage (C8), and the presence of internal decay in trunks (C9) was positively correlated with the leaning (C6) and cavities (C7).

Discussion

In 1929, the street trees in the protected area mainly consisted of *P. stenoptera*, *S. sebiferum*, *P. orientalis*, and *S. japonica* (Yang and Yan, 2013; Yan et al., 2012). Over the past century, the street tree species in the area have undergone constant change. However, due to their strong resistance and longevity, *P. orientalis* and *P. stenoptera* are still present and have become an important part of the historical and cultural heritage of the area. With the construction of high-density buildings, roads, and pipelines, the growth of street trees has become continually disrupted. Coupled with aging, diseases and insect pests, and other causes, these disturbances have caused the trees to become more prone to falling or having broken trunks and branches under extreme weather events such as typhoons (Poulos et al., 2010; Jin et al., 2019). In this context, city managers must make accurate management decisions based on risk assessment. Conventional visual assessment methods mainly detect the growth of the tree canopy and trunk and pest infections in shallow root systems. However, it is difficult to accurately detect internal decay in trunks and the root system with these systems, affecting the accuracy of street tree safety assessments. Accurate detection of internal rot in tree trunks and the proportion of the internal decay in trunks is important; in addition, the distribution of the root system at different depths and ranges can be determined to provide more accurate quantitative indicators for subsequent risk assessments. In this study, we found that the risk level of tree branches of the majority of the street trees in the protected area is low, mainly due to timely management measures; for example, branches that may affect public facilities are annually removed, thereby lowering the possibility of large crown deviation, large dead branches, and diseases and insect pests. Most of the *P. orientalis* trees had a low trunk risk possibility level, while nearly half of the *P. stenoptera* trees had a high trunk risk possibility level, mainly due to internal decay in trunks caused by diseases and insect pests, fungal infestation, and aging(Jia et al., 2021a), which affect the stability of the trees and increase the likelihood that branches and trunks will break. Trees can enhance their wind resistance by moving the root fulcrum (Nicoll and Ray, 1996),. The root system risk level of most of the street trees in the study area is high, mainly because the area available for the trees is small, with poor soil fertility and inadequate growth space for root systems. Moreover, road adjustments and underground pipeline construction often directly cut the root systems of street trees, so certain soil layers contain no roots, and the root systems struggle to support the trees in all directions.

The framework of the street tree safety risk assessment system is based on accurate detection and is essentially similar to traditional visual assessment methods, although the method proposed here uses the internal decay and hollowness of tree trunks and the depth and scope of roots as important assessment indicators, which reduces the subjectivity of the assessment and improves the rationality of the evaluation system (Han, 2013; Jia et al., 2021b). Studies from Hong Kong, Xiamen, and other cities have shown that street trees are affected by the narrow growth space and municipal engineering projects, such as frequent construction and underground trenching (Jim, 2003; Tang, 2018), as well as excessive soil compaction caused by vehicle traffic, all of which can lead to repeated damage to branches and roots and a high probability of tree safety hazards (Jim and Zhang, 2013; North et al., 2017). In this study, we found that more than 74% of the street trees in the protected area have a risk consequence severity level of III or above, indicating severe consequences once the trees are broken. The main reason is that the study area is located in a downtown area with a high building density, high pedestrian and vehicle flows, and narrow sidewalks, and there are interactions among street trees, buildings, and power lines. As a result, cars, buildings, and pedestrians can be exposed to serious risk. However, more than 76% of the street trees have a risk level of II or below, indicating that maintenance and management measures for most of the street trees are in place, resulting in mostly moderate risk possibility levels that are negligible or acceptable. Roads with high risk levels are mostly those with a high road grade, a high building density, or a short distance to buildings as well as parks and green areas near roads with high daily traffic and pedestrian volumes. Taojiang Road, which has a low level of risk, is a small road in an area mainly used for pedestrian traffic, and there is a greater distance between street trees and buildings. The risk assessment method provides valuable information for street tree management in the area and can reduce the risk to a reasonable and acceptable level (He et al., 2021), thereby providing a basis for maintaining the desired vegetation structure of the preserved area in the future.

The results of the VTA-based street tree safety risk assessment of Shanghai City show that the trees in the downtown area of the city are mostly large trees with a heavy canopy load. Due to long-term development in the site environment, the trees exhibit large crown deviation, internal decay in the trunks, and leaning; these issues are concentrated in the branches and trunks (He et al., 2021). The precision diagnosis technique revealed that the main risk points of the street trees are the distribution depth and range of the root systems, belowground pipe gallery construction, and internal decay in the trunks and tree cavities. The results of the correlation analysis indicate that the street tree risk level is strongly correlated with internal decay in the trunks and tree cavities, diseases and insect pests, the distribution range and depth of the root systems, and t1ee leaning. Therefore, in future management of the preserved area, tree height and canopy width should continue to be controlled through daily pruning to avoid potential safety hazards due to excessive tree volume, and further measures should be taken to repair tree cavities and eliminate diseases and insect pests while ensuring that the growth environment of the roots of the street trees is not affected by the construction of pipelines and roads. For street trees with root damage, the range and depth of tree holes should be maximally extended so that the tree roots have sufficient growth space. Moreover, other measures should be used, such as adding supports, to promote healthy tree growth. In addition, regular observations should be conducted, which would allow multiyear detection data to be collected, so that more detailed support can be recommended to improve street tree safety, and a dynamic "planting-monitoring-evaluating-maintaining" management adjustment mechanism should be established.

Conclusion

Based on solving the problem of accurate management of tree safety risk in super large cities. A tree risk detection system including the diagnostic mode of visual tree assessment and nondestructive detection techniques has been constructed, and a risk matrix-based street tree risk assessment system is established with GIS information acquisition and data processing analysis.

An accurate diagnosis technique enables the acquisition of information on the internal decay in trunks and the distribution depth and range of the root system. This information, which cannot be obtained from conventional visual assessments, provides more accurate quantitative indicators for street tree risk assessments. Because of regular tree pruning work, the risk possibility of the tree branches of most of the street trees is low. However, due to insufficient space for root growth and poor soil fertility, the root systems of the street trees in the protected area have a high level of risk. Other causes, such as diseases and insect pests, fungal fruiting bodies, and tree aging, lead to high risk levels in the trunks of some street trees.

The risk possibility and risk level of most of the street trees are low, but a large proportion of the street trees show a high of risk consequence severity level due to the impact of the surrounding environment. Roads with a high street tree risk level are those with a high road grade, a high building density, various public service facilities along the roads with high daily pedestrian flows, or those with trees that are a short distance from buildings.

The main risk points of the street trees in the preserved area include the distribution depth and range of the root system, belowground pipe gallery construction, and internal decay in the trunks and tree cavities. Therefore, the main risk is concentrated in the trunks and roots; these areas should be closely monitored in future management practices, and appropriate corrective measures should be taken.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

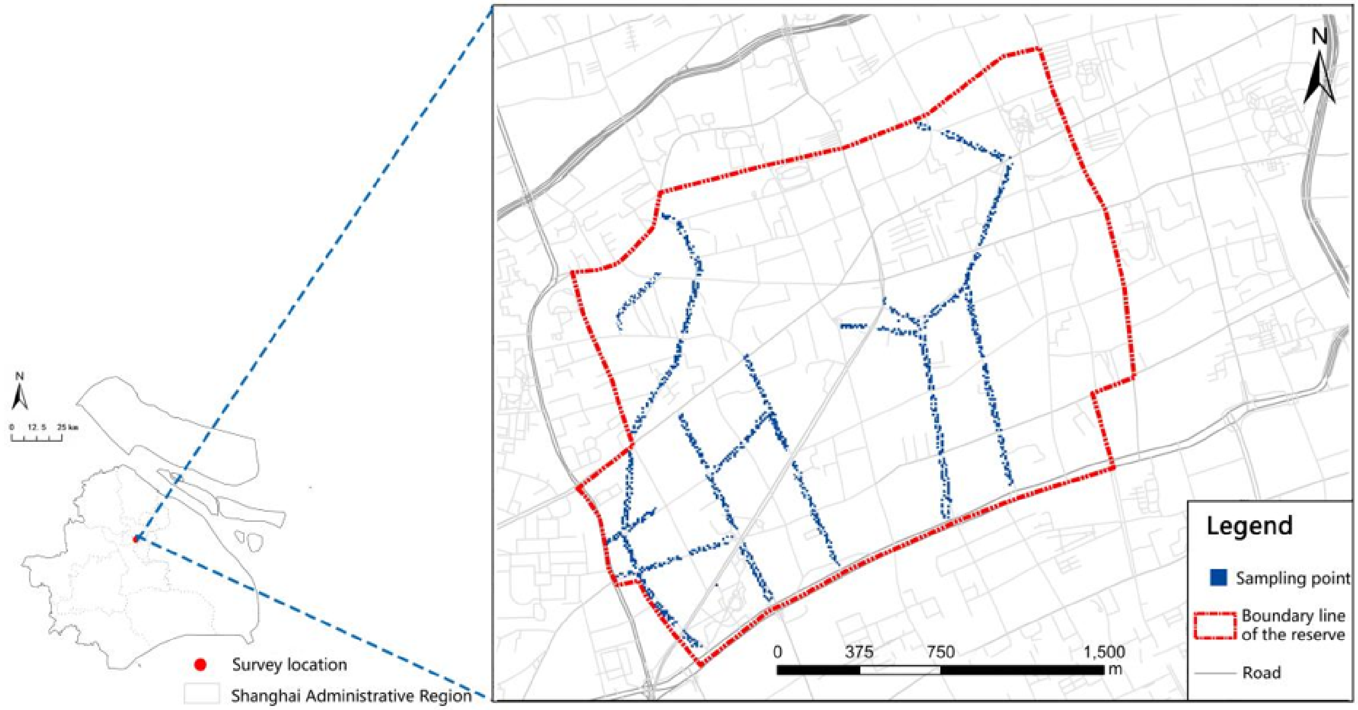

Figure 1

Study area and distribution of sampling points

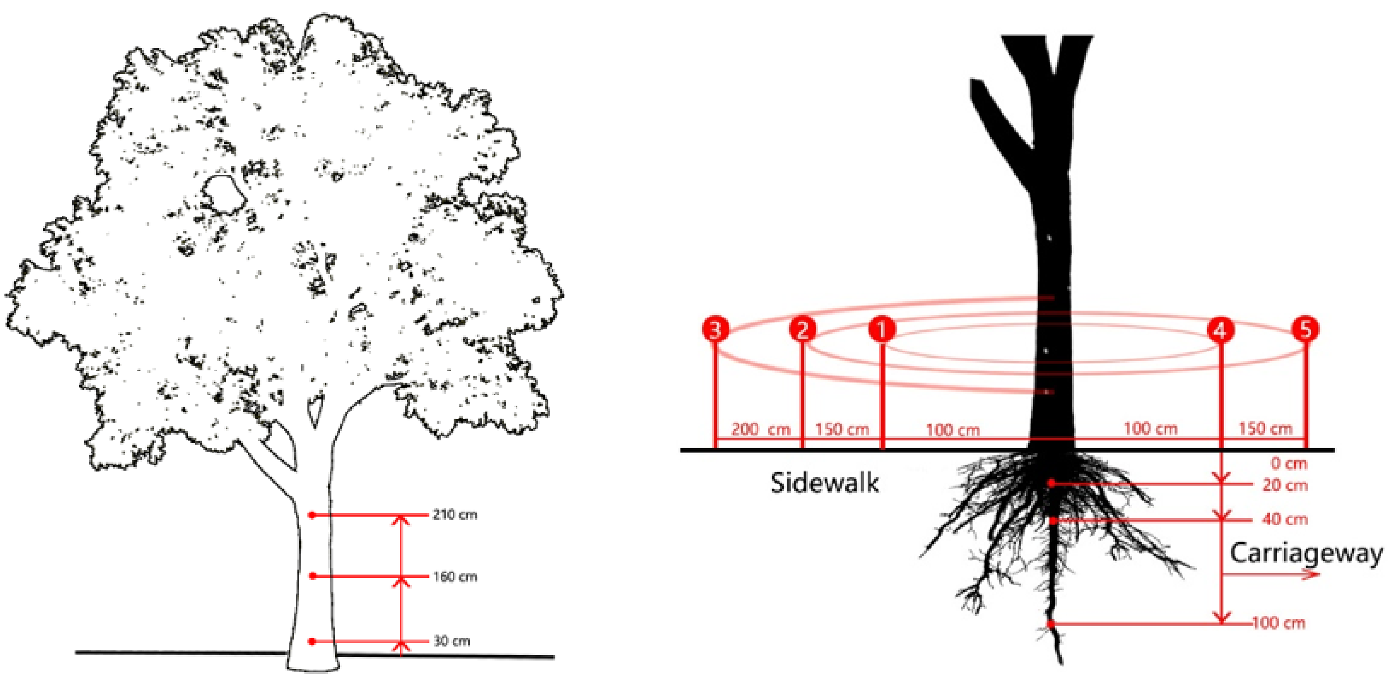

Figure 2

Street tree trunk and root system diagnosis method

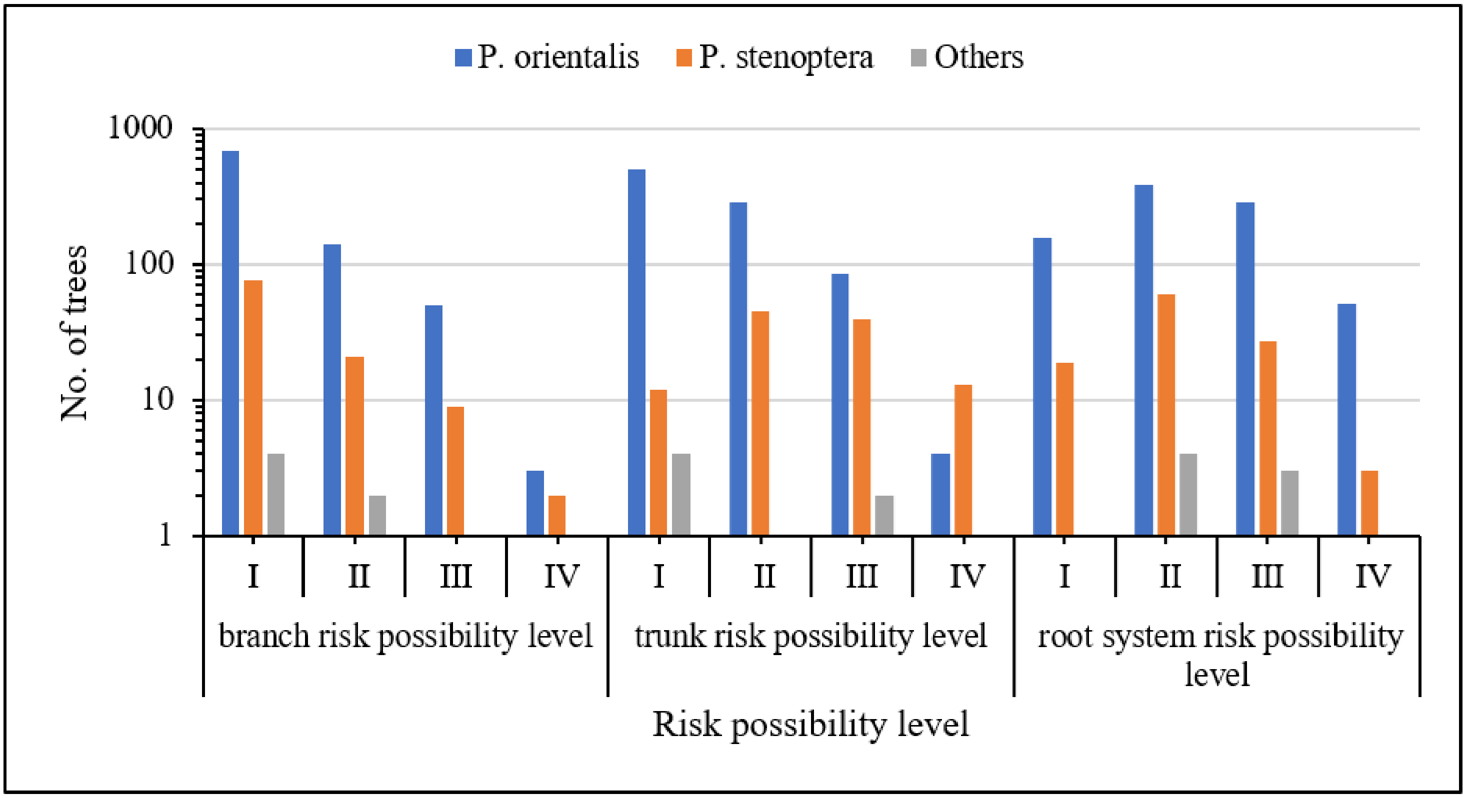

Figure 3

Risk possibility (P) of three parts of roadside tree branches/trunks/roots

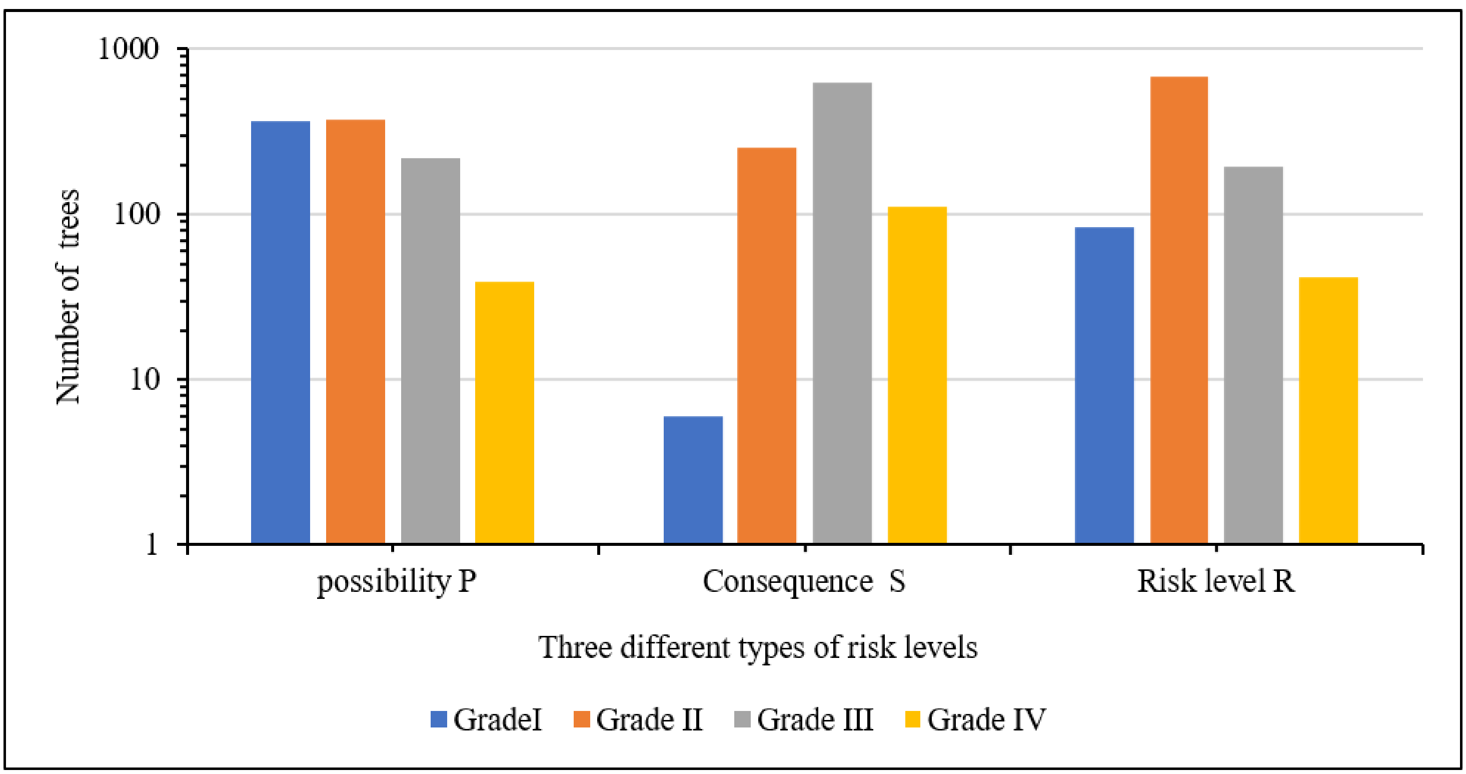

Figure 4

Proportion of the overall safety risk assessment grade of street trees

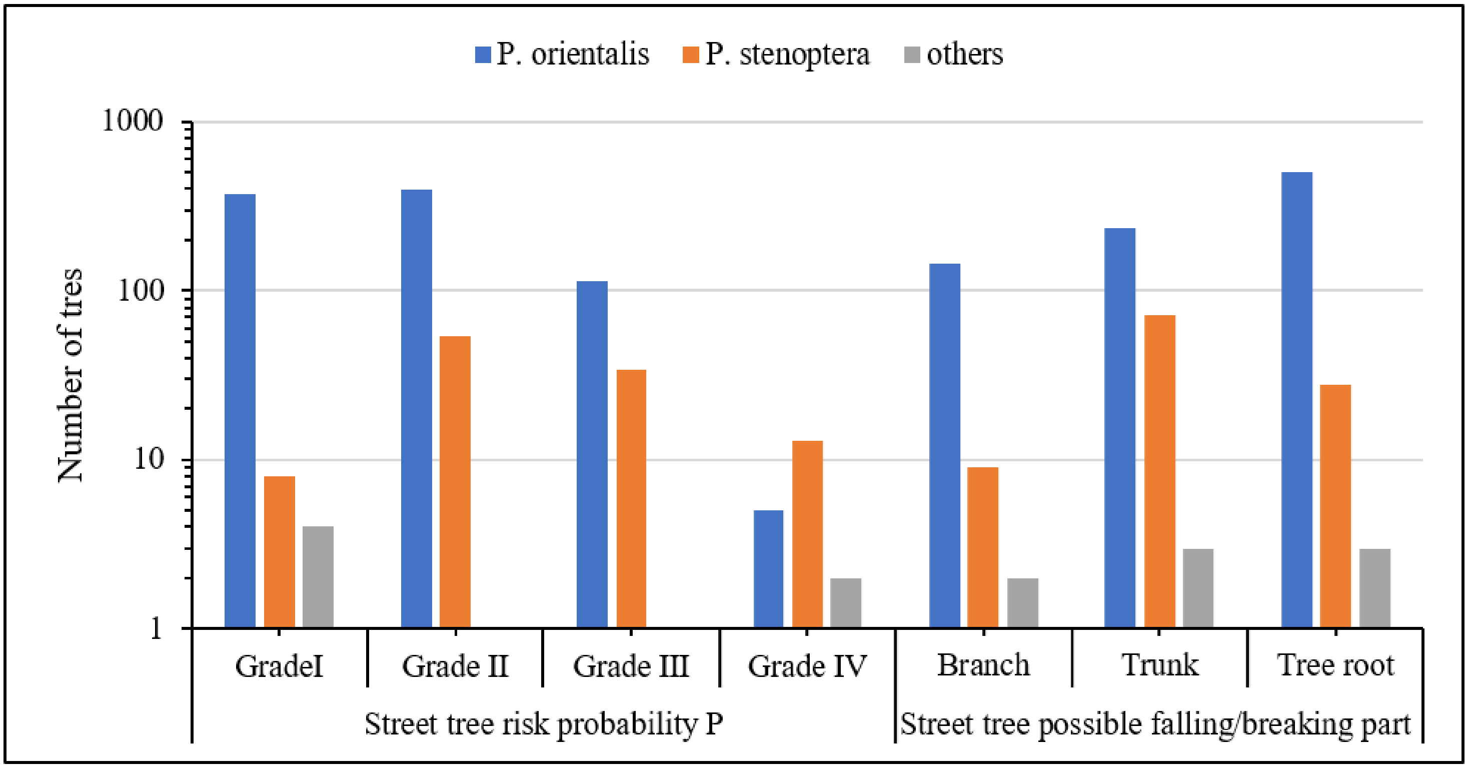

Figure 5

Risk possibility (P) assessment of street tree species

Figure 6

Spatial distribution of street tree safety risk assessment items (Note: Figs. a, b, and c are the spatial distributions of B1, B2, and B3 assessment items, respectively)

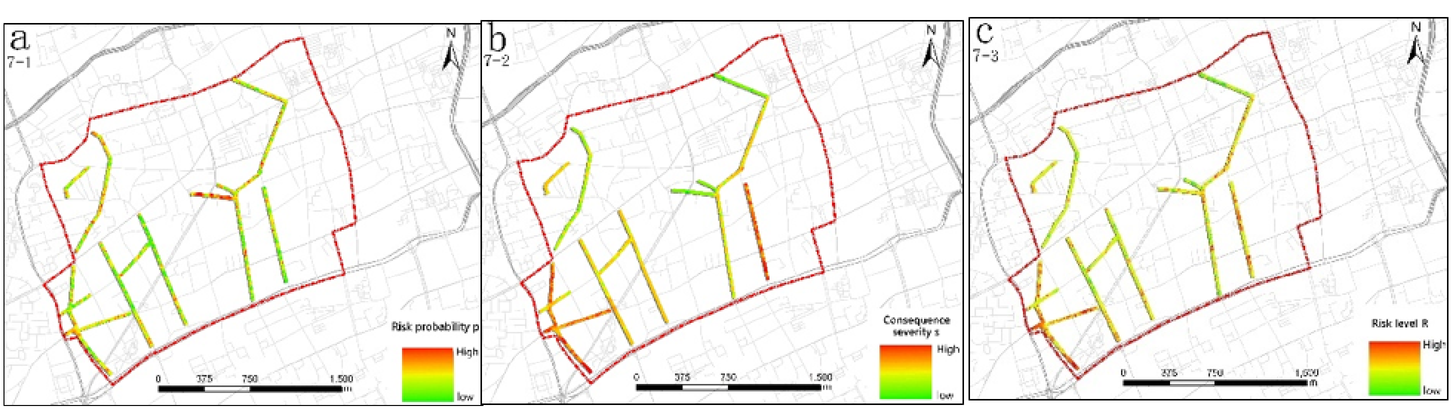

Figure 7

Spatial distribution of safety risk assessment of street trees (Note: Figs. a, b, and c are the spatial distributions of probability level P, severity level S, and risk level R, respectively)

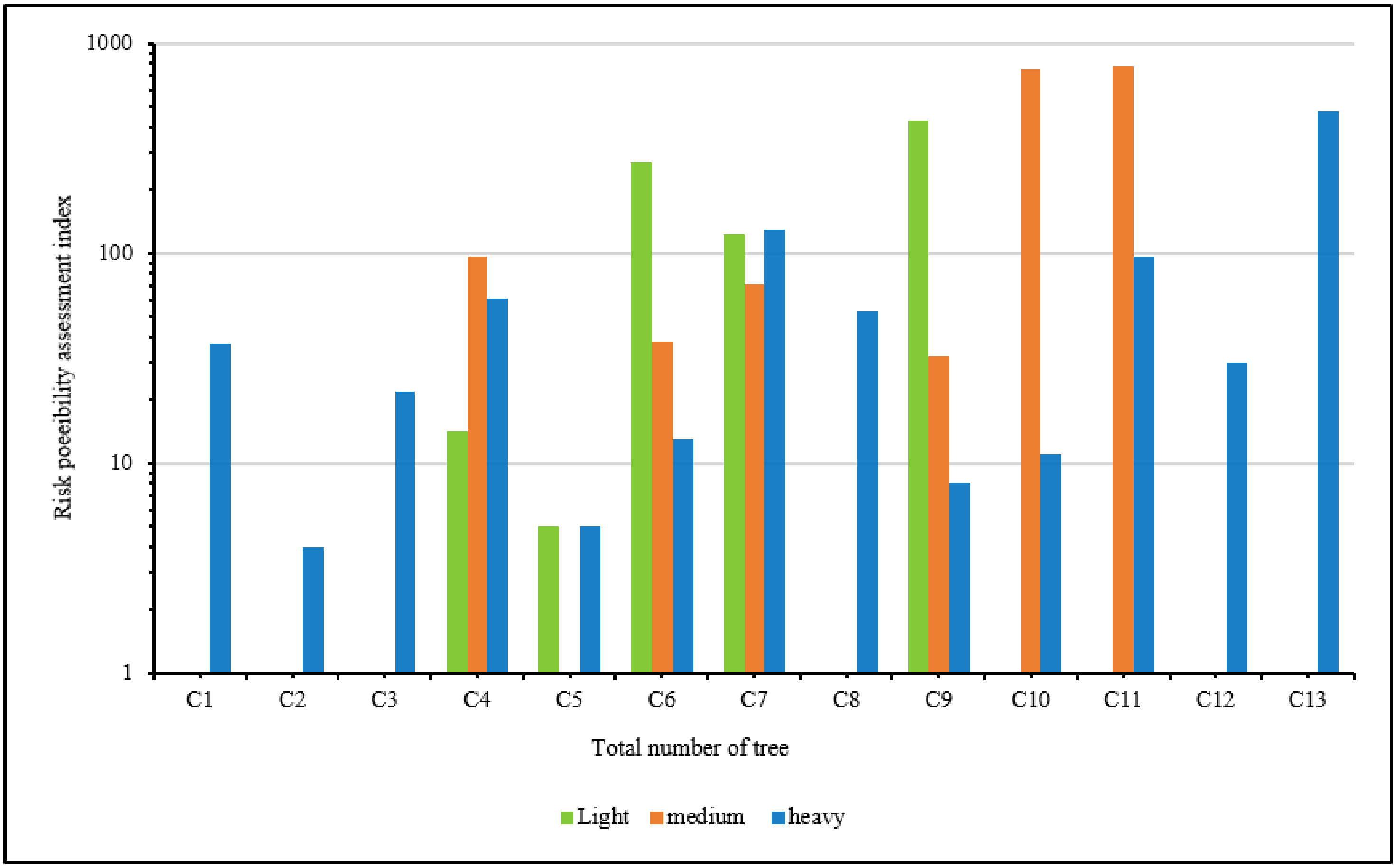

Figure 8

Relationship between the total number of trees (X axis) and the 13 indicators

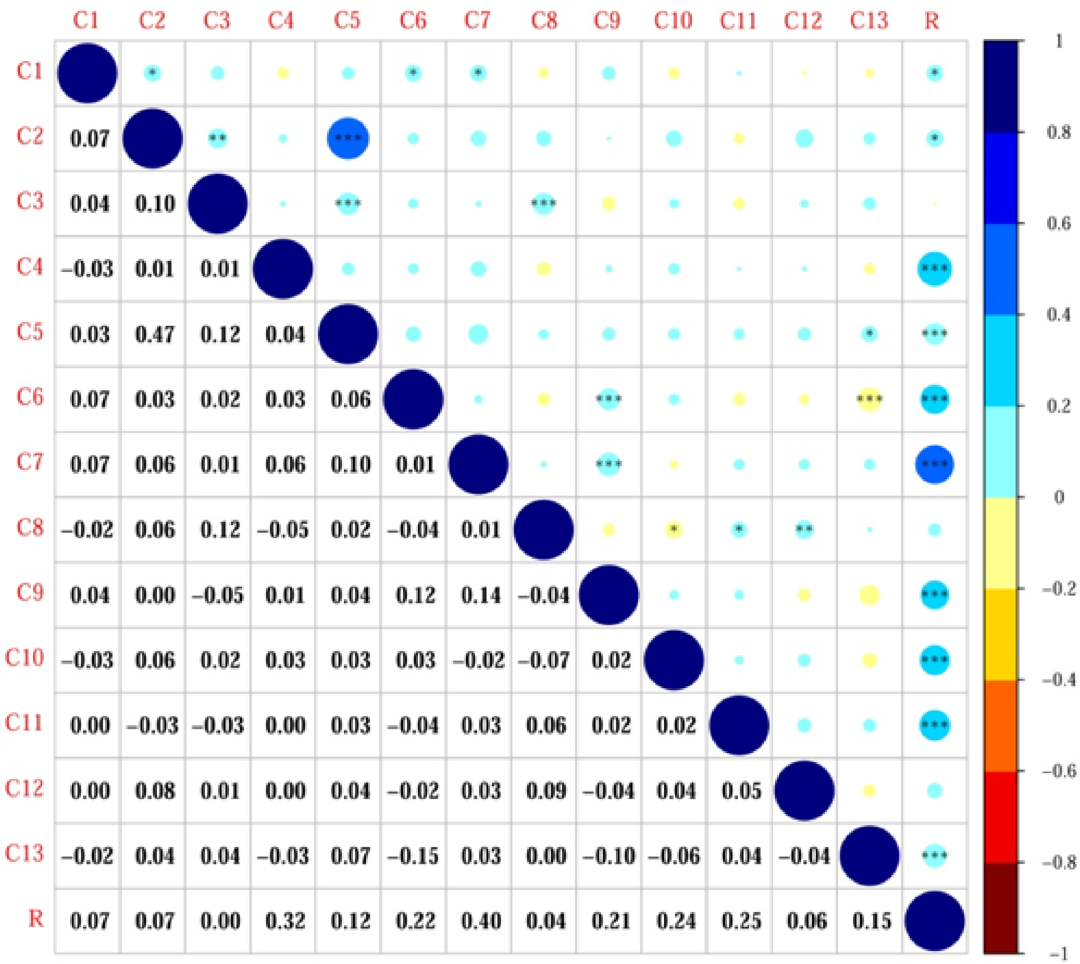

Figure 9

Correlation analysis of the 13 indicators and the R values