

Article

Tree Failure Assessment of London Plane (*Platanus × acerifolia* (Aiton) Willd.) Street Trees in Nanjing City

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Abstract: The London plane (*Platanus × acerifolia* (Aiton) Willd.) street tree is a symbolic tree species in Nanjing City, which is known as the “city card”. However, accidents such as street trees falling over cars, affecting traffic, and hurting people have seriously affected the daily lives of citizens. Thus, it is of vital significance to accurately assess the potential for tree failure in London plane street trees in Nanjing City. This study comprehensively considers the growth condition of London plane street trees and their impact on traffic, establishes a scientific street tree failure assessment scheme that contains eight characteristics, creates a tree failure assessment database by thoroughly collecting data on trees, and develops a tree failure assessment model based on factor analysis and k-means clustering. The assessment results show that street trees that pose a high or medium potential for failure are present in proportions of 4.47% and 34.85%, respectively, and are mostly found in Gulou District, Xuanwu District, and Qinhuai District. The average tree failure score of London plane street trees on Changjiang Road in Xuanwu District is the highest, while the road with the lowest tree failure score is Mufu East Road in Gulou District. The results will provide a scientific basis for the maintenance of London plane street trees in Nanjing City and have reference significance for other street tree failure assessment studies.



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Keywords: tree failure assessment; London plane; street tree; Nanjing city; traffic safety; assessment scheme; factor analysis; k-means clustering

1. Introduction

Urban greening is a crucial component of urban modernization and an essential part of infrastructure [1–3]. Additionally, it is a public welfare undertaking that enhances both the ecological environment [4–6] and life quality of the general population [7]. Street trees are the foundation of urban greening [8], which can play an irreplaceable role in shaping the image of the city and improving the ecological and landscape environment [9–13]. However, affected by the complex urban environment, street trees also have potential safety hazards such as falling branches, broken trunks, and tree lodging, which will pose serious threats to municipal facilities [14], urban traffic [15,16], and the personal safety of citizens [17–19]. The potential of tree failure is based on the presence and severity of the defects, and the tree failure assessment of street trees can detect potential safety hazards in advance [20–22] and help to take targeted maintenance measures to eliminate or reduce safety hazards ahead of time [23–25], which is of great significance to the precision management of urban greening. Therefore, the importance of street tree failure assessment cannot be overstated.

Street tree failure assessment has been studied for several decades [26–30]. A potential tree failure assessment table was first developed based on tree species, size, and structural damage, and then the danger level of trees was determined according to the potential

failure probability, level of harm, and possible targets, which laid the foundation for tree failure assessment [31]. The Visual Tree Assessment (VTA) method was proposed in 1994, which assessed the internal defect level of trees by observing their external appearance and measuring their structural indicators without affecting their health and then evaluated the potential of tree failure, establishing a widely applicable system for tree failure assessment and laying the foundation for other methods developed subsequently [32–34]. For example, the United States Department of Agriculture Forest Services Community Tree Risk Evaluation Method was proposed, which categorized deficiencies into seven categories [35]. And then Best Management Practices-Tree Risk Assessment (ISA/BMP) was developed [36]. Knowing information about the species will improve tree failure assessment; thus, some methods also recommend using failure profiles by species [37]. Besides technologies such as Picus Sonic computed tomography can nondestructively detect the internal structure of trees and accurately determine their health conditions, which is superior to visually using the VTA method [38]. The diagnostic results show precise information about the size and location of decay [39], cavities [40], and damages [41]. These methods are all similar in their assessment of tree structure, defects, and potential hazards; however, differ in how each potential tree failure characteristic is weighed. In addition, as a new technology in the field of landscaping, Geographic Information Systems (GIS) can be used for the tree failure assessment of street trees. For example, the spatial analysis function can be used to explore the spatial distribution pattern of the potential for street tree failure, and the results can also be visualized using maps.

Different tree failure assessment methods exist that take into account biomechanical aspects, site conditions, and weather conditions and have been successfully applied in many cities [42–46]. However, tree failure assessment methods are generally developed to be applicable only in the local environment, and their reliability cannot be guaranteed if used in a different area. All of the basic visual tree failure assessment methods in common use today are qualitative in nature [47]. However, using various visual assessment methods to compare tree failure results, significant differences were found between them [48]. Therefore, although existing methods can play a role in rapid, large-scale urban tree failure assessment, they rely too much on the knowledge of tree professionals in the assessment process, resulting in a certain amount of subjectivity and uncertainty in the final assessment results [26,49]. Moreover, the difficulty of gathering tree failure assessment characteristics is another problem with current studies. Due to the large number of street trees and the strong heterogeneity of the data, it is hard to completely collect information on each street tree. This problem makes many existing studies susceptible to the limitations of small samples and incomplete characteristics. Combined with GIS and mobile mapping, it is helpful to obtain large-scale data and make a comprehensive tree failure assessment of street trees.

London plane (*Platanus × acerifolia* (Aiton) Willd.) is an excellent garden shade tree and street tree in the world, and it is extensively used in urban greening [50–53]. However, there are also some safety hazards in the London plane street tree due to its characteristics. For example, London plane usually has branch points; however, the height of the branch points is low, which makes it easy to cause car collision accidents and affect traffic. In some cases, the branches of London plane are decayed and prone to breakage, resulting in smashing cars and injuring people. Additionally, the trunks of some London plane street trees are inclined, making it easy for the tree to fall [54], which is extremely dangerous. Thus, it is necessary to assess the potential for tree failure in London plane street trees according to their specific characteristics. According to “Nanjing City Street Tree Species Planning (2014–2026)”, there are more than 80,000 London plane street trees in the urban area of Nanjing City, China, making it the main street tree species of the city. The potential for tree failure in London plane street trees in Nanjing City needs to be accurately assessed.

This study aims to comprehensively assess the potential for tree failure in London plane street trees in Nanjing City. In particular, our objectives are to (1) establish a scientific tree failure assessment scheme considering the characteristics of London plane street trees,

(2) create a tree failure assessment database by thoroughly collecting and integrating data of London plane street trees in Nanjing City, (3) develop a tree failure assessment model based on factor analysis and k-means clustering, and (4) map the tree failure potential distribution of London plane street trees in Nanjing City. The results will provide a scientific basis for the management and maintenance of London plane street trees in Nanjing City and have reference significance for other street tree failure assessment studies.

2. Materials and Methods

2.1. Study Area

Nanjing, the capital city of Jiangsu Province in China, is positioned in the middle and lower reaches of the Yangtze River Plain ($118^{\circ}22'–119^{\circ}14'$ E, $31^{\circ}14'–32^{\circ}37'$ N). Located in the subtropical monsoon climate zone, Nanjing City has the distinctive characteristics of four seasons and abundant rainfall year-round. With an average annual temperature of 15.4°C and a relative humidity of 76% [55], the climate of Nanjing City is warm and humid. The study area includes six districts in the main urban area of Nanjing City, i.e., Xuanwu District, Gulou District, Qinhuai District, Jianye District, Yuhuatai District, and Qixia District, covering an area of approximately 782.86 km^2 (Figure 1).

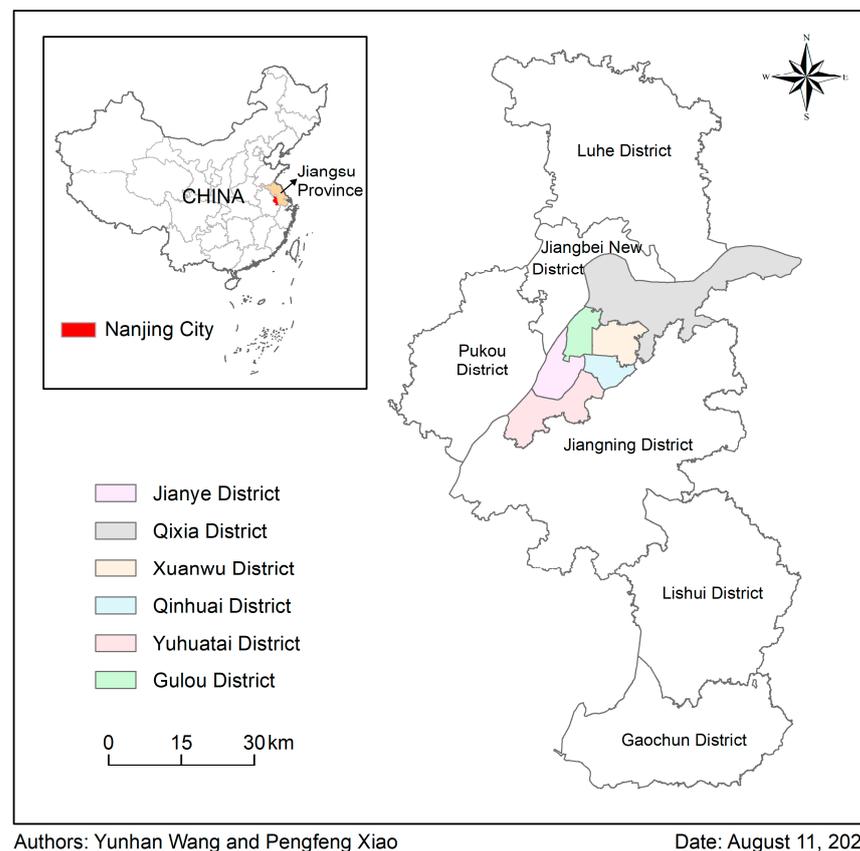


Figure 1. Location and administrative divisions of Nanjing City. The six colored districts in the main urban area of Nanjing City are the study area of this study.

The London plane street tree is a symbolic tree species in Nanjing City, which is known as the “city card”. Due to its lengthy history, which spans more than a century, the London plane street tree has special historical and humanistic meaning to Nanjing City. However, London plane street trees normally have low branch points and lush branches, which can easily result in accidents [56,57]. In recent years, accidents such as London plane street trees falling over cars, affecting traffic, and hurting people by breaking branches have seriously affected the daily lives of citizens in Nanjing City (Figure 2). For example, on 28 April 2021, a London plane street tree suddenly fell down and directly smashed four vehicles

in Nanjing City. According to statistics from the Greening and Landscaping Bureau of Nanjing City, in 2020, there were more than 560 incidents of cars colliding with trees. Thus, it is of vital significance to accurately assess the potential for tree failure in London plane street trees in Nanjing City.



Figure 2. Samples of safety accidents involving London plane (*Platanus × acerifolia* (Aiton) Willd.) street trees in Nanjing City. (a) shows that a London plane street tree fell and damaged a vehicle at the intersection of Baixia Road and Hongwu Road, Qinhuai District, on 28 April 2021 (Image courtesy of Baijiahao). (b) shows that a truck hit a London plane street tree, causing a brunch to get stuck between the cab and the truck box on Baixia Road, Qinhuai District, on 11 July 2022 (Image courtesy of China National Radio News). (c) shows that a truck knocked down a London plane street tree on Ruijin Road, Qinhuai District, on 22 October 2020 (Image courtesy of Modern Express).

2.2. Tree Failure Assessment Scheme for London Plane Street Trees

Tree failure of street trees is closely related to both the own characteristics of trees and external environmental factors, and the characteristics used for tree failure assessment are also various, e.g., tree age, tree vitality, growth location, and site conditions. Among them, the potential for street tree failure is directly related to the tree structure, particularly the growth state of the trunk, crown, and root.

Following the literature review and expert discussion of street tree failure-related characteristics, 25 candidate characteristics are concluded for the tree failure assessment of London plane street trees, which are divided into four categories: overall condition, crown, trunk, and root. Specifically, the overall condition includes three characteristics: tree height, tree vitality, and tree inclination. The crown includes eight characteristics: crown width, crown inclination, dead branches, dead tops, leaf spots or discoloration, disease and insect damage, parasitism, and influence on traffic. The trunk includes eight characteristics: diameter at breast height, xylem cracking, decay, cave damage, disease and pest damage, branch point height, and branch point opening angle. And the root includes six characteristics: damage, growth, aeration, and permeability, loosening, main root exposure or bulging, and decay.

In accordance with the principles of scientificity and operability, characteristics that are less relevant to the tree's failure or difficult to obtain are excluded, such as leaf spots, discoloration, and parasitism. Then, according to the principles of comprehensiveness and systematic optimization, redundant characteristics with similar meanings are removed. Finally, the tree failure assessment scheme for London plane street trees was established, which consisted of eight characteristics (Table 1). The established assessment scheme mainly contains four categories related to the potential for tree failure: growth condition, stability, health condition, and impact on traffic. They depict the threat that street trees pose to municipal facilities, urban traffic, and the personal safety of citizens. Thus, the tree failure assessment scheme developed in this study can comprehensively evaluate the potential for tree failure in London plane street trees and help detect potential safety hazards in advance.

Table 1. Tree failure assessment scheme for London plane (*Platanus × acerifolia* (Aiton) Willd.) street trees.

Category	Characteristic	Definition	Reason for Selection	Field Survey Method
A. Growth condition	A1. Tree height	The height of a tree from root to top.	There is a great correlation between tree height and tree age, and the growth stage of street trees can usually be judged according to tree height. Moreover, compared with the tree age, the tree height is easier to measure, and the data is convenient to obtain.	Tree height is measured using hypsometers.
	A2. Tree vitality	The growth condition of the tree, which can be divided into 5 levels. Trees without records are recorded as 0; trees with lush growth and a complete crown are recorded as 1; trees with normal growth and a basically complete crown are recorded as 2; trees with normal growth and an incomplete or inclined crown are recorded as 3; and trees with abnormal growth and an incomplete crown are recorded as 4. Whether the crown is inclined to one side, which can be divided into two levels. Trees with inclined crowns are recorded as 1, and trees without inclined crowns are recorded as 0.	Tree vitality reflects the overall growth status of street trees, and the possibility of accidents such as the death or falling of street trees with poor tree vitality is high.	Tree vitality is visually assessed by experienced professionals according to level standards.
B. Stability	B1. Crown inclination	Whether the crown is inclined to one side, which can be divided into two levels. Trees with inclined crowns are recorded as 1, and trees without inclined crowns are recorded as 0.	Street trees with inclined crowns are more likely to expose the root or fall.	Crown inclination is visually assessed by experienced professionals.
	B2. Tree inclination	The angle between a tree trunk and the vertical direction.	Street trees with larger inclinations are more likely to fall. In addition, the long-term inclination of the trunk will also affect the growth condition of the tree and the shape of the crown, increasing the possibility of falling. The section of street trees is prone to decay due to rain, erosion, and insects.	Tree inclination is measured using a gradiometer.
C. Health condition	C1. Decay	The proportion of the decayed part of the trunk to the cross-sectional area.	When the rot is deep, the street trees may be partially necrotic or die. At the same time, the characteristic can be obtained by non-destructive testing technology, so the data is convenient to obtain.	Decay is measured using Picus Sonic computed tomography.
	C2. Disease and pest damage	The condition of the disease and pest damage to the trees, which can be divided into four levels. Trees without records are recorded as 0; trees with good growth, no sickness on the trunk and leaves, and no obvious pest damage are recorded as 1; trees with few abnormal leaves and little decayed trunks are recorded as 2; trees with obviously decayed trunks, poor growth of branches and leaves, and many pest damages are recorded as 3.	Diseases and pest damage are the most common problems in maintenance and management, which will damage the health of street trees or tree structures and threaten the health of street tree groups in serious cases.	Disease and pest damage are visually assessed by experienced professionals according to level standards.
D. Impact on traffic	D1. Branch point height	The height from ground level to the first living branch point of the tree.	If the branch point height of the street tree is too low, it may cause safety accidents such as car collisions with the tree, affecting the traffic safety of the roadway and sidewalk.	Branch point height is measured using hypsometers.
	D2. Branch point opening angle	The angle between the two branches above the first branch point.	If the branch point opening angle of the street tree is too large, it is easy to break branches due to external forces or the change of its own load-bearing structure [58], endangering the safety of pedestrians and traffic.	Branch point opening angle is measured using a gradiometer.

2.3. Tree Failure Assessment Database of London Plane Street Trees

London plane street trees are numerous and distributed all around Nanjing City. Advanced investigation and observation technology are required to assist in the full gathering of data for each London plane street tree. It is necessary to use data from different sources and different modes to establish the tree failure assessment database for London plane

street trees. The data source consists of five components: the Nanjing City street tree survey database, the dangerous street tree database, the street tree lidar point cloud and panoramic image database, the street tree maintenance records, and the sampling survey in the field by our team members.

Tree height (A1) and tree vitality (A2) are collected from the Nanjing City Street Tree Survey Database. Currently, there are no directly available data on crown inclination (B1), tree inclination (B2), branch point height (D1), or branch point opening angle (D2). Based on the street tree lidar point cloud and panoramic image database of Nanjing City, we use lidar point cloud and panoramic image measurement technology to obtain these data. Compared with field surveys, this mobile mapping technology has the advantages of fast measurement speed and low cost. Decay (C1) can be acquired from the dangerous street tree database of Nanjing City. Since many London plane street trees are aging and have weak tree vitality, the proportion of London plane street trees in the dangerous street tree database is much higher than 20%. Thus, a significant amount of information on the decay degree of London plane street trees can be gathered. According to the street tree maintenance records in Nanjing City, data on disease and pest damage (C2) can be obtained. In addition, some tree failure assessment characteristics of London plane street trees are measured in the field through the sampling survey. Comparison and validation with the acquired data are carried out to check whether there is any mismeasurement or omission of the characteristics, and the database is updated to improve the accuracy and integrity of the assessment data.

Finally, we constructed the tree failure assessment database for the London plane street trees in Nanjing City. Through the thorough collection and integration of data on London plane street trees, a total of 14,775 data points are collected, which are distributed on 103 roads. The data can be used for street tree failure assessment after data cleaning and standardization.

2.4. Tree Failure Assessment Model of London Plane Street Trees

2.4.1. Factor Analysis

Factor analysis is a multivariate statistical analysis method that starts from the dependence relation within the correlation matrix of the variables and condenses the variables with overlapping information and intricate relations into a few irrelevant comprehensive factors. The fundamental concept of factor analysis is to group variables according to their correlation, so that the correlation between variables in the same group is high while the correlation between variables in different groups are irrelevant or low. Each group of variables represents a basic structure, that is, a common factor. On the premise that much of the original information is retained, factor analysis can eliminate the correlation between the original variables, reconstruct a new interpretable common factor, and obtain the weight of each variable, which objectively reflects the relative importance of each variable.

Assuming that the observation system has m factors and p observations, the statistical model of factor analysis expresses the p observations as the linear weighted sum of $m < p$ common factors and a special factor, as shown in Equation (1).

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_p \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_p \end{bmatrix} + \begin{bmatrix} \alpha_{11} & \alpha_{12} & \dots & \alpha_{1m} \\ \alpha_{21} & \alpha_{22} & \dots & \alpha_{2m} \\ \vdots & \vdots & & \vdots \\ \alpha_{p1} & \alpha_{p2} & \dots & \alpha_{pm} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_m \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_p \end{bmatrix} \quad (1)$$

where F_1, F_2, \dots, F_m are unobserved common factors, which are usually independent of each other; α_{pm} is the coefficient of the p variable on the m common factor, called the factor load, which reveals the relative importance of the p variable on the m common factor; and ε_i is a factor unique to each corresponding variable, X_i , which is called a special factor and cannot be included in the common factors. Their relation is shown in Equations (2)–(4).

$$\text{cov}(F, \varepsilon) = 0 \quad (2)$$

$$D(F) = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{bmatrix} = I \quad (3)$$

$$D(\varepsilon) = \begin{bmatrix} \sigma_1^2 & & & \\ & \sigma_2^2 & & \\ & & \ddots & \\ & & & \sigma_p^2 \end{bmatrix} \quad (4)$$

where F and ε are independent; F_1, F_2, \dots, F_m are independent of each other and the variance is 1; and $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_p$ are independent of each other and the variance is not necessarily equal. It is usually assumed that $\varepsilon_i \sim N(0, \sigma_i^2)$.

2.4.2. K-Means Clustering

K-means clustering is a widely used unsupervised iterative algorithm. The basic idea of k-means clustering is to divide a given dataset into K categories according to the principle that the intra-class distance is as small as possible and the inter-class distance is as large as possible according to the distance between the data.

The specific steps of the k-means clustering are as follows: Firstly, the number of division categories K is predetermined, and K objects $\{a_1, a_2, \dots, a_K\}$ are randomly selected as the initial cluster centers of the given n data $\{x_1, x_2, \dots, x_n\}$. Then, calculate the distance between each data point and each cluster center and assign the data to each cluster center according to the principle of the closest distance. Finally, recalculate each category center to minimize the square sum of the distance W_n between each data point and the nearest cluster center, as shown in Equation (5).

$$W_n = \sum_{i=1}^n \min_{1 \leq j \leq K} |x_i - a_j|^2 \quad (5)$$

2.4.3. Tree Failure Assessment Model

Based on the tree failure assessment scheme of London plane street trees, the assessment characteristic data is first tested, and then common factors are extracted by factor analysis to objectively determine the weight of each characteristic. Following that, a comprehensive tree failure score for each tree is obtained by weighted calculation. Finally, according to k-means clustering, the potential for London plane street tree failure is divided into three levels: low-potential, medium-potential, and high-potential.

- (1) Assessment characteristic data test: KMO and Bartlett's tests are carried out on the characteristic data of 14,775 London plane street trees. The KMO value is 0.549, and Bartlett's test of sphericity has a Sig. of 0.000 when the degree of freedom is 28, which reaches a significant level. The test results prove that factor analysis can be performed on the tree failure assessment characteristics.
- (2) Common factor extraction: Principal component analysis is used to extract the first six common factors with a cumulative contribution rate of 86.854%, which can explain most of the information about all characteristics.
- (3) Factor loading matrix extraction: The orthogonal rotation method of maximizing variance is used to rotate the original factor load matrix, and the variance ratio explained by each factor is redistributed to make the meaning of common factors clearer. The rotation converges after 6 iterations, resulting in the sum of squares of the rotated loadings and the rotated factor loading matrix.
- (4) Tree failure score calculation: The rotated factor loading matrix is divided by the square root of the corresponding eigenvalue to produce the common factor score

coefficient matrix. Each common factor score is calculated according to the common factor score coefficient matrix, as shown in Equation (6).

$$\begin{aligned}
 F_1 &= -0.095A1 + 0.579A2 + 0.017B1 - 0.032B2 + 0.551C1 - 0.049C2 - 0.013D1 + 0.038D2 \\
 F_2 &= +0.414A1 - 0.075A2 + 0.853B1 - 0.093B2 + 0.039C1 + 0.144C2 - 0.064D1 - 0.113D2 \\
 F_3 &= +0.353A1 - 0.040A2 - 0.162B1 - 0.027B2 + 0.071C1 + 0.090C2 - 0.151D1 + 0.896D2 \\
 F_4 &= -0.232A1 - 0.097A2 + 0.179B1 - 0.004B2 + 0.040C1 + 0.927C2 + 0.027D1 + 0.090D2 \\
 F_5 &= -0.067A1 - 0.024A2 - 0.040B1 - 0.008B2 - 0.009C1 + 0.013C2 + 1.040D1 - 0.128D2 \\
 F_6 &= -0.083A1 - 0.019A2 - 0.062B1 + 1.019B2 - 0.040C1 - 0.015C2 - 0.005D1 - 0.010D2
 \end{aligned} \tag{6}$$

where $A1, A2, B1, B2, C1, C2, D1, D2$ are the standardized data for each characteristic.

Finally, the variance contribution rate of each common factor is used as the characteristic weight to carry out the weighted summation to obtain the comprehensive score F of the tree failure assessment of each street tree. The calculation formula is shown in Equation (7).

$$F = 0.076A1 + 0.104A2 + 0.181B1 + 0.073B2 + 0.159C1 + 0.165C2 + 0.083D1 + 0.128D2 \tag{7}$$

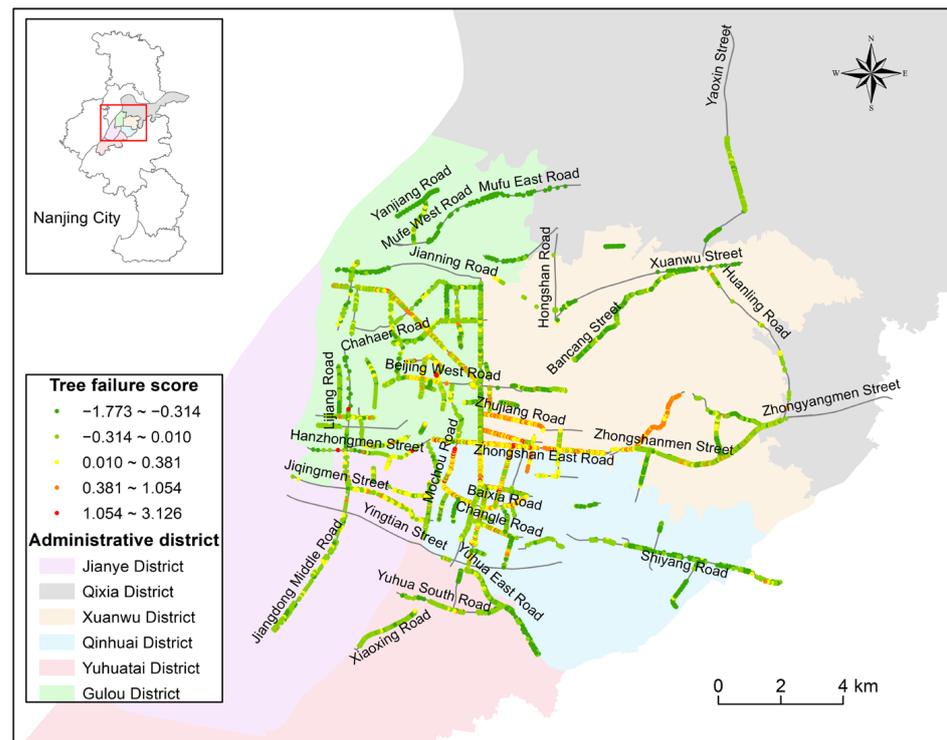
- (5) Tree failure level assessment: According to the “Classification Standards of Dangerous Trees of Nanjing Street Trees” [59] and the “Technical Regulations for Health Diagnosis of Urban Trees” (DB11/T 1692-2019 [60]), the tree failure scores of street trees are divided into three categories by k-means clustering. According to the tree failure score, the three categories are determined as low-potential, medium-potential, and high-potential. The score of low-potential London plane street trees ranges from -1.77 to 0.01 ; the score of medium-potential London plane street trees ranges from 0.01 to 0.78 ; and for high-potential London plane street trees, the score ranges from 0.78 to 3.13 .

3. Results

3.1. Tree Failure Score Distribution of London Plane Street Trees

The tree failure scores of 14,775 street trees are calculated based on Equation (7), ranging from -1.77 to 3.13 . The higher the tree failure score, the greater the potential for tree failure. The roads with higher tree failure scores of London plane street trees are in Qinhuai District, Gulou District, and Xuanwu District (Figure 3). Among them, the average tree failure score of London plane street trees on Changjiang Road in Xuanwu District is the highest, which is 0.70 . Roads with an average tree failure score greater than 0.4 include Zhujiang Road (Xuanwu District), Mochou Road (Qinhuai District), Santiao Alley (Qinhuai District), Jiankang Road (Qinhuai District), and Lingyuan Road (Xuanwu District), which means that the potential for tree failure on these roads is generally high. While the road with the lowest tree failure score is Mufu East Road in Gulou District, which has an average tree failure score of -0.64 . Yanjiang Road (Gulou District), Mufu West Road (Gulou District), Heyan Road (Gulou District), Jianning Road (Gulou District), and Gongqingtuan Road (Yuhuatai District) all have an average tree failure score that is less than -0.5 . The London plane street trees on these roads pose a low potential for tree failure.

The London plane street tree with the highest tree failure score is located on Zhujiang Road, Xuanwu District, with a tree failure score of 3.13 . It has an inclined crown, seriously decayed branches, and severe damage from diseases and pests. These factors may increase the potential for tree falls and broken branches, affect traffic, interfere with the daily lives of residents, and even put personal safety at risk. The lowest potential for London plane street tree failure is located on Gongqingtuan Road, Yuhuatai District, with a tree failure score of -1.77 . The tree has good vitality, a suitable tree height, no inclined crown, almost no inclination of the trunk, no pests and diseases, no decayed branches, and no branch points; thus, the potential for tree failure is low.



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Figure 3. Tree failure score distribution of London plane street trees in Nanjing City.

3.2. Tree Failure Level Distribution of London Plane Street Trees

The tree failure assessment model for London plane street trees divides all trees into three levels, including 661 high-potential street trees, 5120 medium-potential street trees, and 8994 low-potential street trees. That is, the proportions of high, medium, and low-potential street trees are 4.47%, 34.85%, and 60.87%, respectively, and their clustering centers are 1.27, 0.28, and -0.25 .

The characteristics of the trees with different levels of potential for tree failure clearly differ, while the same-level trees exhibit comparable traits. The score of low-potential London plane street trees ranges from -1.77 to 0.01 . Generally, these trees are in good vitality, with almost no crown inclination, slight branch decay, less disease and pest damage, a small opening angle at the branch point, and no obvious inclination of the trunk. The score range of medium-potential London plane street trees is 0.01 – 0.78 , and their characteristics are slightly worse than those of low-potential trees. For high-potential London plane street trees, the score ranges from 0.78 to 3.13 . These trees commonly have poor vitality, seriously decayed branches, inclined crowns, and overall poor conditions in other aspects.

The tree failure level distribution of London plane street trees is shown in Figure 4. A total of 49 roads have high-potential street trees, mostly distributed in Gulou District and Xuanwu District, among which Changjiang Road has the largest number of high-potential trees (89). Medium-potential street trees are mostly distributed in Gulou District and Qinhuai District. There are medium-potential trees on 90 different roads, and Zhongshan East Road contains the largest number of them (509). In addition, all of the 103 roads are covered with low-potential street trees, among which Zhongshanmen Street has the highest number.

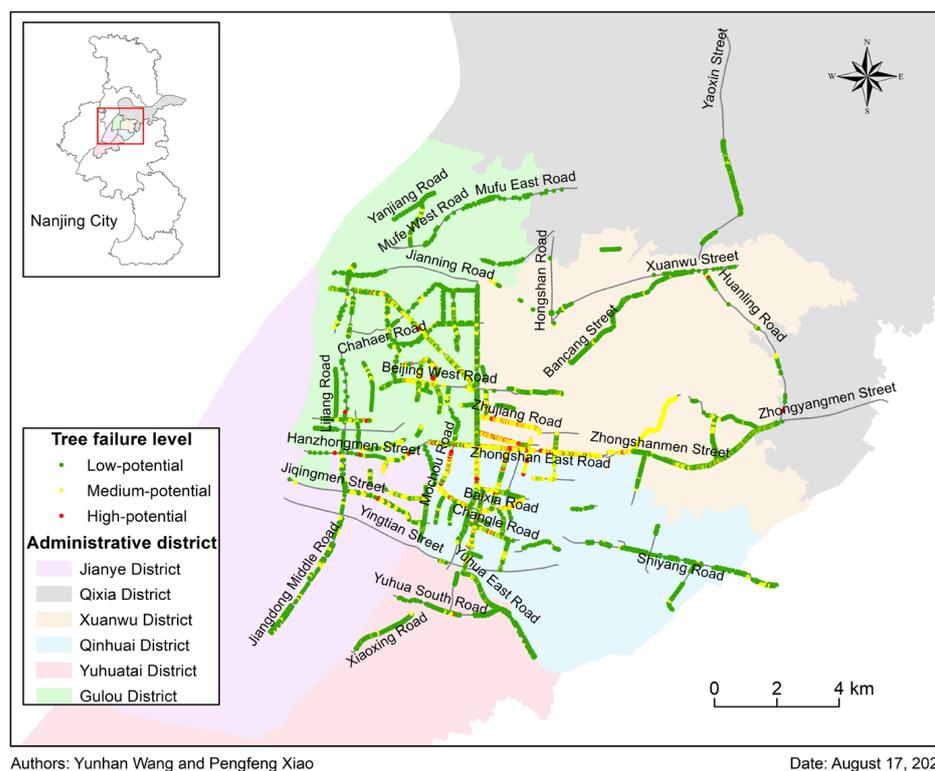


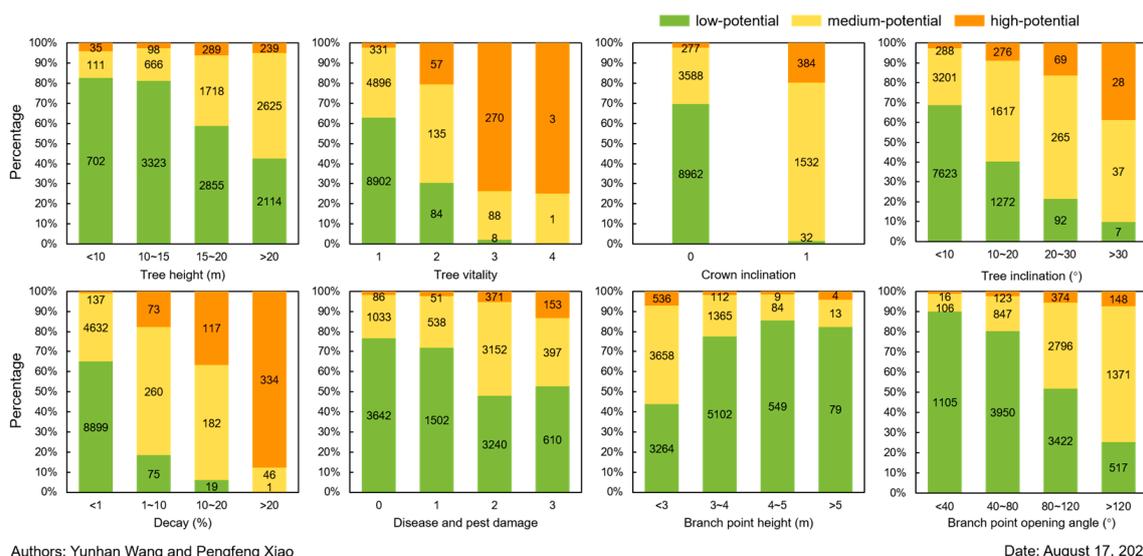
Figure 4. Tree failure level distribution of London plane street trees in Nanjing City.

3.3. Relation between Tree Failure and Assessment Characteristics

The value of the assessment characteristics has a great influence on the tree failure level of London plane street trees. The relationship between tree failure and assessment characteristics is revealed to provide suggestions for street tree maintenance. According to the calculation formula of the tree failure score (Equation (7)), the corresponding weight coefficients of eight tree failure assessment characteristics can be obtained, which can reflect the relative importance of each characteristic to the tree failure levels of London plane street trees. The ranking of importance of assessment characteristics in descending order is as follows: crown inclination (B1), disease and pest damage (C2), decay (C1), branch point opening angle (D2), tree vitality (A2), branch point height (D1), tree height (A1), and tree inclination (B2). Furthermore, the proportion of all characteristics in the three tree failure levels is calculated to determine the threshold of each characteristic under different tree failure levels (Figure 5). The crown inclination (B1) is the most important characteristic in the tree failure assessment. If the trees have inclined crowns, the percentage of high-potential trees is 19.71%, and the percentage of trees with low potential is even lower than 2%. The importance of disease and pest damage (C2) to the tree failure assessment of London plane street trees is second only to that of crown inclination. If the level of disease and pest damage is over 2, the percentage of high-potential and medium-potential street trees is higher than 50%. Decay (C1) is also crucial for assessing the potential of tree failure. If the proportion of the decayed part of the trunk to the cross-sectional area is more than 20%, the percentage of trees with high potential even reaches 87.66%.

3.4. High-Potential London Plane Street Trees

For the tree failure assessment of London plane street trees, the specific situation of high-potential street trees deserves the most attention. According to the above results, there are 661 high-potential London plane street trees, accounting for 4.47% of the total number. It is necessary to further analyze the conditions of high-potential London plane street trees, which are conducive to subsequent targeted maintenance measures.



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Figure 5. Relation between the tree failure level and each characteristic of London plane street trees. The numbers in the columns indicate the number of street trees.

Roads with more than 30 high-potential trees include Changjiang Road, Zhongshan East Road, Zhujiang Road, Zhonghua Road, Zhongshanmen Street, and Zhongshan North Road. The percentage of high-potential trees on each road is also calculated, and Changjiang Road, Santiao Alley, Mochou Road, and Zhujiang Road are the roads with the highest percentages (more than 20%). The dominant tree failure characteristics of high-potential trees on these roads are analyzed by calculating the mean value of each characteristic on the road. For Changjiang Road, the most serious problem for high-potential trees are crown inclination, with 95.51% of high-potential trees having inclined crowns. The characteristic of disease and pest damage is also important on Changjiang Road, with an average level of three. Trees on Zhujiang Road have large opening angles at the first branch point, the mean value of which reaches 114.78°. In addition, the average level of disease and pest damage is three on Zhujiang Road, which is also severe. Tree inclination is a significant issue on Zhonghua Road, affecting 70.73% of the high-potential trees there. High-potential trees on Zhongshanmen Road are generally tall, with an average tree height of 19.49 m. The branches of trees on Zhongshan North Road have a great degree of decay, and the average proportion reaches 21.43%. For Santiao Alley, the tree vitality and tree inclination of high-potential trees are both poor. The mean level of tree vitality is three, and the average angle between the tree trunk and the vertical direction is 20.67°. On Mochou Road, high-potential trees have a mean proportion of decaying branches that reaches 29.15%, which has a great influence on tree failure. To lessen the safety hazard posed by London plane street trees, it is necessary to develop maintenance and management strategies for these roads based on their dominant characteristics.

4. Discussion

4.1. Implication

The main implication of this study lies in three aspects: (1) the usability of the integrated tree failure assessment database; (2) the transferability of the tree failure assessment scheme and model; and (3) the guidance for the maintenance and management of London plane street trees in Nanjing City.

A high-quality tree failure assessment database of London plane street trees is built by collecting and integrating data from multiple sources. The database contains information on 14,775 London plane street trees located along 103 roads in the main urban area of Nanjing City. With the help of the database management platform and mobile mapping technology, some of the data needed for assessment are obtained by using lidar point clouds and panoramic image measurement, which greatly improves the working efficiency and

reduces the cost. At the same time, the field sampling survey is used to verify and update the characteristic data of London plane street trees, so as to further improve the authenticity, validity, and reliability of the database. The established database can not only be used for the tree failure assessment of London plane street trees but can also be transferred and applied to similar studies, such as the health status assessment of street trees.

This study establishes a scientific, comprehensive, and easy-to-apply tree failure assessment scheme and model for London plane street trees that is portable and can be extended to other street tree failure assessment studies. Among all the characteristics selected for tree failure assessment, crown inclination plays a significant role, which is in correspondence with previous studies [61]. Trees with inclined crowns are more likely to fall on their heavy sides [62], and crown inclination is one of the best explanatory characteristics for tree damage [63]. Disease and pest damage are other relatively important characteristics for tree failure assessment in this study. The health condition of street trees can be significantly affected by disease and pest damage [64,65], and heavily damaged trees are more likely to break branches and fall down, causing safety hazards. Moreover, the tree failure assessment scheme and model developed in this study can fully realize the combination and complementarity of subjective prior knowledge and objective reality, improve the validity of comprehensive assessment while being scientific and practical, and obtain accurate tree failure assessment results for London plane street trees in Nanjing City.

Taking Nanjing City as an example, the accurate tree failure assessment results of London plane street trees are obtained based on the data of 14,775 street trees distributed on 103 roads. London plane street trees in Nanjing City with a high tree failure score or level are mostly distributed in Xuanwu District, Gulou District, and Qinhuai District. This result is in high agreement with other studies [57]. Besides it has been demonstrated that Xuanwu District, Gulou District, and Qinhuai District are administrative areas with a high frequency of accidents on London plane street trees in Nanjing City [56], which also reflects the correctness of the result from this study since high-potential street trees are more likely to cause safety accidents. Moreover, visualization with maps can improve the effectiveness and readability of the potential for tree failure information for London plane street trees. The spatial analysis function of GIS is used to visualize the assessment results, and the tree failure assessment map is drawn to express the location, distribution, and tree failure level of London plane street trees in Nanjing City, so as to satisfy the needs of spatial cognition of the potential of tree failure of London plane street trees. The results provide reference information for the maintenance, planning, management, and other related decisions of London plane street trees in Nanjing City. In addition, this study can offer fundamental information for studies on the urban ecological environment and administration of urban planning in Nanjing City.

4.2. Limitations and Future Perspectives

The core of street tree failure assessment is to develop a scientific street tree failure assessment scheme. This study thoroughly analyzes the growth condition, stability, health condition, and impact on traffic of London plane street trees and establishes a scientific tree failure assessment scheme. However, it is equally crucial to consider how the growing environment of street trees affects their potential for failure. The data related to the growth environment of street trees, such as soil conditions, road grades, number of windy days, main wind directions, and man-made projects, is currently hard to collect on a large scale. In the future, relevant environmental data can be supplemented to further improve the study. Besides qualitative indicators were used for crown inclination data due to the technical limitations of the data collection. This may introduce subjectivity and uncertainty into the assessment results. Specifically, the importance of crown inclination (B1) ranks first in the tree failure assessment; however, this high importance may be related to the quantification of the characteristic. In future studies, the crown inclination should be measured in degrees. Moreover, the study provides a snapshot of the potential for tree failure at a given time. As tree health and structural conditions change over time, ongoing monitoring is essential.

Future studies could adopt longitudinal approaches to observe changes in tree failure potential and assess the effectiveness of intervention strategies.

5. Conclusions

This study establishes a scientific London plane street tree failure assessment scheme with eight characteristics that comprehensively considers the growth condition of street trees as well as their impacts on traffic. Based on technologies including GIS and mobile mapping, a tree failure assessment database is created by thoroughly collecting and integrating multisource data. Additionally, a tree failure assessment model is developed using factor analysis and k-means clustering. Based on data from 14,775 street trees on 103 roads in Nanjing City, accurate tree failure assessment results for London plane street trees were obtained. Specifically, the main results are: (1) street trees that pose a high or medium potential level are present in proportions of 4.47% and 34.85%, respectively, and are mostly found in Gulou District, Xuanwu District, and Qinhuai District; (2) the average tree failure score of London plane street trees on Changjiang Road in Xuanwu District is the highest, while the road with the lowest tree failure score is Mufu East Road in Gulou District; and (3) crown inclination, disease and pest damage, and decay are the top three characteristics that have the largest effects on the potential of tree failure of London plane street trees in Nanjing City. In conclusion, the tree failure assessment of London plane street trees in Nanjing City sheds light on critical dimensions of urban safety. The analysis of tree failure scores, categorization of tree failure levels, relation between tree failure and assessment characteristics, and identification of high-potential trees collectively underline the imperative of systematic tree management for urban safety enhancement. The findings of this study can serve as a foundation for the maintenance and management of London plane street trees, as well as fundamental knowledge for urban ecological environment studies and urban planning in Nanjing City. By addressing the potential for tree failure in street trees, cities can not only enhance the physical safety of their residents but also contribute to the aesthetic and environmental vitality of their urban landscapes.

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