# Integrated Health Assessment and Support Strategies for Ancient Trees in Cultural Heritage Sites Based on Non-Destructive Testing

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**Abstract**

Ancient trees, as carriers of cultural and ecological heritage, are vulnerable to diseases caused by aging and environmental stress, leading to structural degradation and loss of heritage value. Traditional detection methods are limited in identifying internal cavities and root system decline, and existing evaluation systems often rely on external indicators, resulting in incomplete assessments. This study develops a multi-dimensional approach for disease detection and precise diagnosis, along with a health assessment index system incorporating physiological and ecological parameters for comprehensive evaluation. Tree radar was used to detect and quantify internal trunk cavities, complemented by crown dieback, bark damage, and shallow root indicators, forming a concise health evaluation framework. Ten scoring indicators were applied to classify tree health into four levels: healthy, weak, severely weak, and critical. Field research on century-old trees within the Zhengjue Temple area of Beijing's Old Summer Palace showed most trees fell into the "weak (Grade B)" category. Further analysis revealed canopy degradation positively correlated with cavity rate, while shallow roots and trunk inclination significantly affected stability. Based on these findings, targeted support strategies, including trunk bracing, root ventilation, and pest control, were proposed. The study demonstrates the feasibility of using non-destructive testing for health assessment and reinforcement planning, providing a practical reference for the conservation of ancient trees in cultural heritage sites.

## 1. Introduction

Ancient trees, typically over one hundred years old, possess important ecological functions and rich historical and cultural value. In heritage sites, they are both part of the landscape and records of history. However, as they age, they are vulnerable to pests, trunk cavities, and root degradation, threatening their health and structural stability. Therefore, scientifically and comprehensively assessing their health is central to their conservation.

Various assessment methods have been developed in academia. Liu et al. (2017) employed variance analysis and multiple comparison methods to explore the causes and limiting factors of tree health differences. Shao (2020) used a tree growth indicator system to evaluate external morphology and appearance. An (2013) applied stress wave technology to assess internal tree health. Some scholars have investigated the dominant factors affecting ancient tree health from hydrological, meteorological, soil, and microbial perspectives. Recently, non-destructive testing (NDT) techniques have expanded the tools available for health assessment. For example, Peng et al. (2021) applied tree radar to detect trunk cavities in street trees; Liu et al. (2017) studied ancient Platycladus orientalis, finding cavity rates negatively correlated with crown width, crown area, and crown height ratio, but positively correlated with diameter at breast height and crown asymmetry. Zheng et al. (2013) explored the relationship between risk assessment and management, establishing an assessment–management framework. Lan (2021) used VTA and AHP to develop a multi-level, multi-dimensional risk evaluation system, while Lian et al.


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(2024) applied entropy weighting and factor analysis to establish a health assessment system for Docynia trees.

Despite these advances, most existing evaluation systems focus on external indicators and lack quantitative assessment of critical internal factors such as trunk cavities. This limitation may lead to biased results, failing to accurately reflect overall tree health. Traditional methods, including visual inspection and simple physical testing, provide some external information but are limited in diagnosing internal structural damage, particularly cavities and root degradation.

To address these issues, this study introduces advanced tree radar and other NDT techniques to detect and quantify internal trunk cavities, while combining external indicators such as crown dieback, bark damage, and shallow roots to construct a concise yet comprehensive health evaluation system. Using century-old trees in the Zhengjue Temple area of Beijing's Old Summer Palace as a case study, the research systematically assesses their health and proposes targeted support and maintenance strategies, including trunk bracing, root ventilation, and pest management. This study aims to validate the feasibility of NDT and integrated evaluation methods for ancient tree conservation, providing technical guidance for the scientific maintenance and sustainable protection of trees in cultural heritage sites.

## 2. Study Area Overview

The study area is located in Haidian District, Beijing, at 116°18′E, 40°00′N, and belongs to a typical temperate monsoon climate zone, with an average elevation of approximately 50 meters. The annual mean temperature is about 12.6°C,with extreme highs reaching 40.6°C in July and extreme lows dropping to -16°C.The annual precipitation ranges from 600 to 700 mm, mainly concentrated in summer, particularly from June to August, accounting for approximately 60% of the yearly total, while winters are relatively dry. These climatic conditions are suitable for the growth of ancient trees, especially species such as pine and cypress.

## 3. Materials and Methods

### 3.1. Study Objects

In October 2024, a survey was conducted on the ancient trees of Zhengjue Temple, located within the Yuanmingyuan Ruins Park in Haidian District, Beijing. A total of 30 surviving ancient trees were recorded, belonging to five species: Chinese scholar tree (Sophora japonica), Chinese juniper (Juniperus chinensis), Chinese arborvitae (Platycladus orientalis), Chinese white pine (Pinus bungeana), and black jujube (Ziziphus jujuba var. spinosa).The trees have diameters at breast height ranging from 42 to 118 cm, heights between 8 and 22 m, and ages from 80 to 350 years. Among them, one is classified as a first-class ancient tree, while the others are second-class.

The survey revealed that most of the ancient trees within the courtyard exhibit signs of decline, such as weakened vigor and bark shedding. Notably, one ancient Platycladus orientalis shows severe trunk inclination (Figure. 1a), and one ancient black jujube displays surface cavities (Figure. 1b). The remaining trees also exhibit varying degrees of decline. If large internal cavities exist within their trunks, the risk of wind-induced breakage or collapse would be significantly increased. Therefore, it is essential to detect trunk decay in these ancient trees, assess their health conditions in conjunction with external indicators, and propose targeted support and conservation measures.

(a) (b)

Figure 1. Characteristic Images of Ancient Tree Diseases (a) Trunk inclination of an ancient Platycladus orientalis (oriental arborvitae);(b) Surface cavity on the trunk of an ancient Ziziphus jujuba (Chinese jujube).

### 3.2. Detection of Internal Trunk Cavities

The internal cavities of the ancient trees were detected using the TRU Tree Radar system (Figure 2), a non-destructive testing technology based on ground-penetrating radar principles. This system efficiently identifies internal trunk cavities and cracks, as well as the depth and distribution of root systems, providing reliable and intuitive data for assessing the health status of ancient trees. Compared with traditional drilling or visual inspection methods, TRU Tree Radar does not damage the tree structure during detection, ensuring the safety of ancient trees while improving inspection efficiency.

A 900 MHz radar antenna was used to scan the trunks at multiple heights:1.1, 1.3, 1.5, and 1.7 m.At each height, scanning was performed clockwise around the trunk starting from the north, with two full rotations per height. The measuring wheel was kept in constant contact with the bark to ensure smooth movement, and the radar scanning plane was maintained as parallel and close to the trunk as possible. The data with the strongest signals and highest clarity were selected as samples.

Data processing was conducted using Tree Radar’s proprietary TBA analysis software. The raw radar data were filtered and the detection thresholds adjusted to clearly identify and mark abnormal signals in the interference images. This allowed accurate detection of cavity areas and their extents, generating cross-sectional diagrams at different heights of the same trunk that display the cavity areas and orientations, as shown in Figure 3.

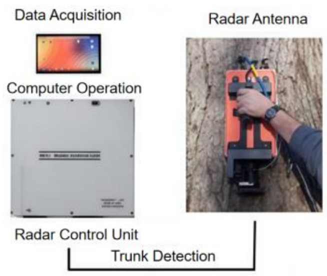


Figure 2. TRU Tree Radar Detection System.

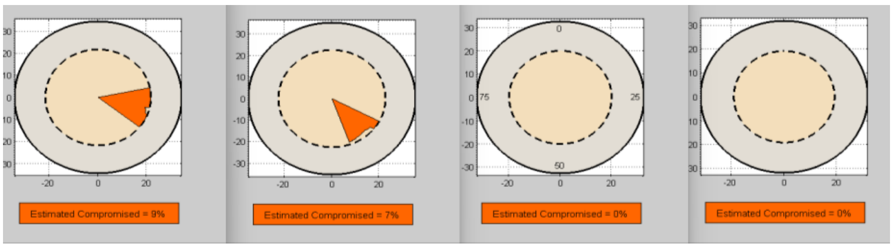


Figure 3. Cavity distribution at different heights of the same trunk.

The assessment of internal trunk cavities in ancient trees was conducted by comparing radar detection images and data at different heights. The cavity rates of cross-sections at four heights of the trunk were denoted as P1、P2、P3、P4, with the total cavity rate defined as $P=P1+P2+P3+P4$ and the average cavity rate as $P'=P/4$. According to the method of Xiao et al. (2017), the cavity condition of ancient tree trunks is classified into four levels: Level I (no cavity) with $P'=0$, Level II (slight cavity) with $0<P'\leq 25\%$, Level III (moderate cavity) with $25\%<P'\leq 50\%$, and Level IV (severe cavity) with $50\%<P'\leq 100\%$, as shown in Table 1.By integrating the cavity rates across different heights, a more accurate evaluation of trunk structural integrity and stability can be achieved, providing a reliable basis for subsequent support and maintenance strategies.

| Cavity Level | Indicator% | Description of Tree Characteristics |
|---|---|---|
| I | 0 | Trunk structure intact, wood hard and dense, no signs of decay, physiological functions fully normal |
| II | 0-25 | Localized initial decay present, but main load-bearing structure intact, mechanical strength not significantly affected |
| III | 25-50 | Decay areas noticeably expanded, some wood becoming loose, trunk mechanical performance beginning to decline, reinforcement measures required |
| IV | 50-100 | Severe decay, trunk structural integrity lost, risk of toppling present, immediate emergency protection or removal required |

Table 1. Classification of Ancient Tree Trunk Cavity Levels

### 3.3. Ancient Tree Health Assessment

This study, drawing on the research of Ying (2011) and Weng et al. (2009) and following the indicator selection and scoring principles outlined in the Technical Guidelines for Rapid Diagnosis of Ancient and Famous Trees, employed the Analytic Hierarchy Process (AHP) to construct a multi-dimensional, multi-level health assessment system for ancient trees. The system comprises a total of five primary indicators and ten secondary indicators. The scoring criteria for each indicator are presented in Table 2, and the corresponding indicator weights are listed in Table

| Primary indicators | Secondary indicators | Individual indicator grading | | | |
|---|---|---|---|---|---|
| | | I（None） | II（Light） | III（Moderate） | IV（Severe） |
| Leaf | Crown leaves showing withering and yellowing（%） | ＜60 | 60-75 | 75-90 | ＞90 |
| Trunk | Bark exhibiting cracks, lesions, or peeling （%） | ＜5 | 5-15 | 15-30 | ＞30 |
| | Trunk inclination （°） | < 5 | 5-10 | 10-15 | ＞15 |
| | Internal trunk decay level （%） | 0 | 0-25 | 25-50 | 50-100 |
| Branches | Proportion of dead or broken branches (%) | ＜5 | 5-15 | 15-20 | ＞20 |
| Roots | Number of exposed roots | 0 | 0-1 | 2-3 | ＞3 |
| | Shallow or underdeveloped roots (＞60cm) | ＞10 | 10-7 | 7-3 | 3-0 |
| Environment | Interference from surrounding buildings (m) | ＞10 | 10-3 | 3-1 | ＜1 |
| | Human disturbance （v/m2） | 0 | 0-10 | 10-30 | ＞30 |
| | Pest and disease infestation（%） | ＜5 | 5-15 | 15-30 | ＞30 |

Table 2. Grading Table of Health Assessment Indicators for Ancient and Famous Trees

| Assessment Item | Assessment indicators | Scoring criteria | | | |
|---|---|---|---|---|---|
| External | Crown leaves showing withering and yellowing（%） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Bark exhibiting cracks, lesions, or peeling（%） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Trunk inclination （°） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| Internal | Internal trunk decay level（%） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Proportion of dead or broken branches（%） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Number of exposed roots | None（3） | Light（2） | Moderate（1） | Severe（0） |
| Internal | Shallow or underdeveloped roots（＞60cm） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Interference from surrounding buildings（m） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Human disturbance（v/m2） | None（3） | Light（2） | Moderate（1） | Severe（0） |
| External | Pest and disease infestation（%） | None（3） | Light（2） | Moderate（1） | Severe（0） |

Table 3. Scoring Table of Health Assessment Indicators for Ancient and Famous Trees

Based on the data of the above indicators, the health assessment score for each ancient tree was calculated, and the specific grade classification is shown in Table 4.

| Overall Score | Health Level | Description of Ancient Tree Health Status |
|---|---|---|
| 26-30 | Normal（A） | The ancient tree has an overall healthy growth condition, with no diseases or pests. It is lush and leafy, and its trunk is free from damage. |
| 16-25 | Weak（B） | The ancient tree occasionally has withered leaves or branches falling off, and there are slight signs of diseases or pests. Additionally, its trunk has partial damage. |
| 6-15 | Blighted（C） | The ancient tree has suffered severe damage, exhibits poor ability to adapt to the external environment, and shows an overall poor growth condition. |
| 0-5 | Endangered（D） | The ancient tree exhibits an overall poor growth condition, with numerous signs of withering and damage. It is severely affected by diseases and pests, and the tree is already in a moribund state. |

Table 4. Health Classification of Ancient and Famous Trees

## 4. Results and Analysis

### 4.1. Results and Analysis of Hollowing in Ancient Trees

Based on tree radar detection, 21 of the 30 ancient trees in Zhengjue Temple (70%) exhibited hollowing, mostly mild (67%), with only one case of moderate hollowing and none of severe hollowing. Analysis of the relationship between tree age and hollowing confirmed that age is a key factor, as mild hollowing commonly occurs during aging. However, species differences are significant; for example, a 330-year-old Chinese arborvitae maintained nearly intact wood structure, likely due to defensive compound accumulation. These findings highlight the need for species-specific management strategies to effectively slow down hollowing in ancient trees.

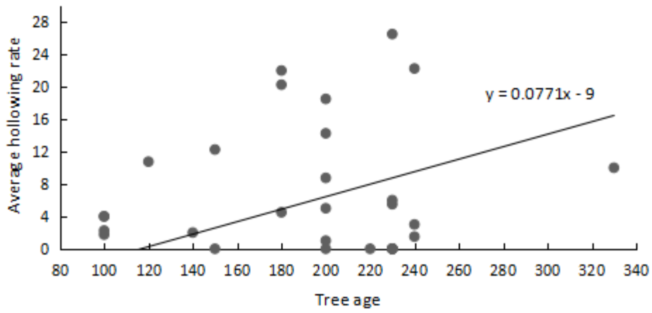


Figure 6. Relationship model between tree age and average hollow rate.

### 4.2. Analysis of Health Status in Ancient Trees

Statistical analysis showed that all 30 ancient trees were classified as weakened (Grade B), with occasional leaf loss, minor pests or diseases, and partial trunk damage. No significant correlation was found between tree age and health score, indicating that age alone is not decisive for health. Some old trees remained healthy under good maintenance and habitat conditions, while some younger trees declined due to environmental stress. A comparison of hollowing rate and health score further revealed that hollowing alone has limited impact on overall health; trees with similar hollowing levels often differed significantly in health due to variations in pest control, root condition, and crown vigor. These results highlight the need for a comprehensive multi-parameter health assessment system that integrates structural, physiological, and ecological indicators to guide targeted conservation strategies.

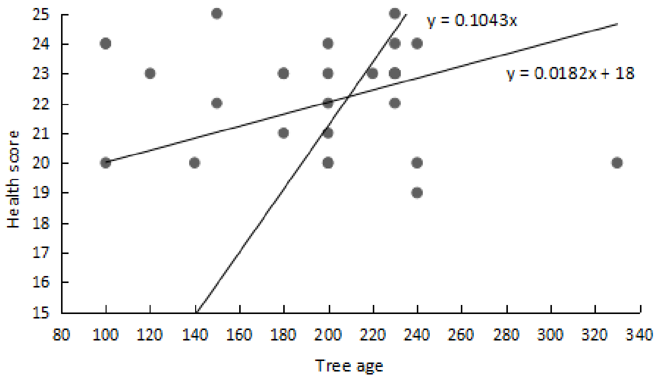


Figure 7. Relationship Model between Tree Age and Health Score.

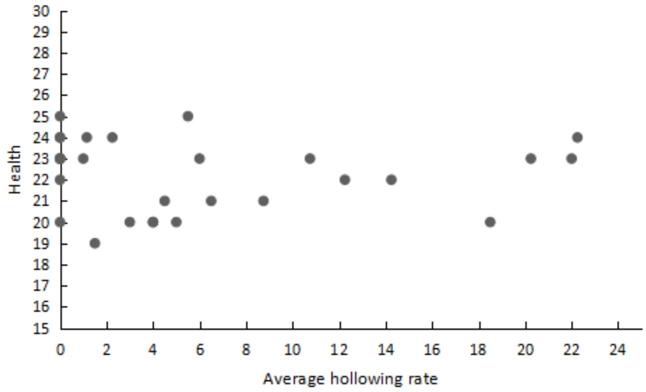


Figure 8. Relationship Model between Average Hollowing Rate and Health Score.

## 5. Conclusions and Discussion

This study used tree radar to assess 30 ancient trees in Zhengjue Temple, Yuanmingyuan, and found a hollowing occurrence rate of 70%, predominantly mild, with very few moderate cases and no severe hollowing. Although the hollowing rate generally increased with age, species differences were significant; for instance, a 330-year-old Chinese arborvitae maintained intact wood structure, highlighting the role of species traits. No significant correlation was observed between age and overall health, as proper maintenance could sustain old trees while environmental stress often degraded younger ones. Hollowing, though an important structural indicator, showed limited influence on health compared with pests, root condition, and crown vigor. Accordingly, a graded protection strategy is proposed: preventive care for trees without hollowing, repair and monitoring for mildly hollowed trees, and structural reinforcement with ecological restoration for moderately hollowed trees. In addition, a "one tree, one file" digital management system and professional maintenance team are recommended to enable continuous monitoring, annual evaluation, and adaptive management, ensuring scientific, precise, and sustainable conservation that preserves both the ecological and cultural value of ancient trees.

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