Non-Destructive Evaluation and Failure Prediction of Tree Branches: An Integrated Review

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Abstract - *Urban and roadside trees are biological structures that simultaneously provide ecological services and present mechanical hazards when stems, branches, or root plates fail. Internal decay, cavities, cracks, weak branch unions and changes in wood properties may remain hidden during routine visual inspection. This review synthesizes the uploaded literature on non-destructive evaluation (NDE) of standing trees and links diagnostic measurements to engineering-based failure prediction. Visual assessment and three-dimensional surveys are effective first-line screening tools, while stress-wave/ultrasonic methods provide information on stiffness-related changes and internal discontinuities. Acoustic tomography can map cross-sectional anomalies, electrical resistance tomography can be particularly informative in early decay, and resistance microdrilling can localize and differentiate defects when tomographic shadows are ambiguous. Infrared thermography offers rapid non-contact screening of thermal anomalies, whereas ground-penetrating radar provides electromagnetic sensing but has shown species- and geometry-dependent limitations. Recent stand-off radar combined with deep learning demonstrates a pathway toward rapid, contactless population-scale screening. Mechanical pulling tests and tree statics complement NDE by translating defect information into load–capacity considerations. The evidence supports a staged, multimodal workflow in which rapid screening is followed by targeted internal characterization and, where required, mechanical validation. The principal research need is an uncertainty-aware fusion of sensor data, tree geometry, material properties and environmental loading into a defensible probability-of-failure framework.*

Key Words: Tree failure; Non-destructive evaluation; Acoustic tomography; Stress wave; Resistograph; Ground-penetrating radar; Infrared thermography; Tree statics; Deep learning.

1. INTRODUCTION

Tree failure is governed by an interaction between applied loads, tree geometry, material properties and the condition of the load-bearing structure. Wind, snow, ice and self-weight generate bending and overturning demands, while decay, cavities and cracks reduce the effective structural capacity. Engineering-based tree statics therefore considers the load, the load-bearing surface and the material properties together rather than interpreting residual wall thickness in isolation [1,12]. Finite-element modelling of root anchorage under wind loading has further shown that progressive root breakage can govern uprooting resistance and can be incorporated into failure simulations [19]. Pulling experiments on mature Acer trees showed that codominant-stem failures can occur at substantially lower stress than stem failures [11], while later static-pulling work on silver birch demonstrated the usefulness of loading-resistance measurements for comparing tree stability in urban and peri-urban settings [23].

The central challenge is that a visually acceptable tree may contain hidden defects. Conventional boring or coring provides only local information and can create wounds through which decay organisms may spread [10,12]. Consequently, a broad family of NDE techniques has been developed, including visual assessment, stress-wave timing, acoustic/ultrasonic tomography, resistance drilling, ground-penetrating radar (GPR), electrical resistance tomography (ERT), infrared thermography (IRT), remote sensing and mechanical pull testing [1]. These methods do not measure the same physical quantity; rather, they sense density, elastic response, electrical properties, temperature, geometry or structural response. Their outputs must therefore be interpreted according to the defect type, species, moisture condition, geometry and inspection objective [8].

2. TREE FAILURE MECHANISMS AND DIAGNOSTIC REQUIREMENTS

Three broad failure modes are relevant to stems and branches: bending or shear failure of the stem, failure of branch or codominant unions, and root-plate overturning. Internal decay reduces wood density and stiffness and may also alter the effective section geometry. Cracks can be especially problematic because they interrupt wave paths and may create tomographic shadows larger than the physical crack [3,4]. Branch-attachment morphology also has a direct mechanical role: experimental testing found that branch-to-trunk diameter ratio was a strong predictor of breaking stress, with failure behaviour influenced by attachment form and included bark [20]. The diagnostic requirement is therefore not simply to detect an anomaly, but to estimate its location, extent, type and influence on residual capacity.

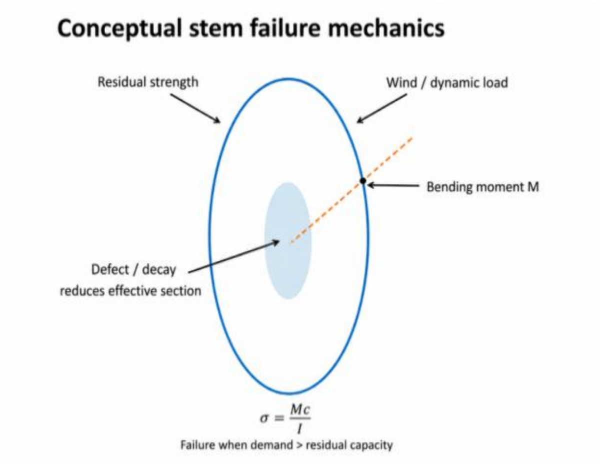

Fig -1. Conceptual relationship between environmental loading, defect-induced loss of capacity and stem failure.

3. NDE TECHNIQUES FOR TREE STEMS AND BRANCHES

3.1 Visual inspection and geometric sensing

Visual Tree Assessment remains the logical first step because it is rapid and can reveal external cavities, fungal fruiting bodies, cracks, included bark, abnormal butt swell and crown symptoms. However, visual assessment is qualitative and cannot directly quantify hidden decay or residual wall thickness [1]. Recent reviews show that terrestrial laser scanning (TLS), mobile laser scanning and photogrammetry can improve measurement of stem diameter, taper, branch architecture and surface damage. TLS offers high geometric detail, whereas photogrammetry is more affordable and portable but is sensitive to illumination, image overlap and atmospheric conditions [14]. Terrestrial LiDAR has also been demonstrated for quantitative reconstruction of branch architecture [21], while low-cost photogrammetry has been shown capable of reconstructing trunks and lower-order branches relevant to sway monitoring and structural-stability assessment [22]. These methods are therefore particularly valuable for measuring the geometry required by subsequent mechanical calculations rather than for directly imaging internal decay.

3.2 Stress-wave and ultrasonic evaluation

Stress-wave testing uses the travel time of an impact-generated wave between sensors. Because wave velocity is related to the elastic properties of wood, increased travel time can indicate decay, cracks or cavities [1,2]. In a study of 168 standing western hemlock and Sitka spruce, in-situ stress-wave measurements showed good agreement with stress-wave properties of small clear specimens and significant relationships with static bending properties at the 0.01 level [2]. This establishes stress-wave measurements as useful indicators of wood stiffness and strength variation, although species, moisture, grain direction and local anatomy influence the response. Ultrasonic tomography studies have additionally demonstrated that multiple travel-time measurements can be used to locate and estimate defect regions in standing trees, supporting the use of ultrasonic methods as a complementary high-resolution diagnostic tool [17].

Single-path timing is efficient but provides only a path-integrated indication. Multi-sensor tomography overcomes this limitation by collecting numerous paths around a cross-section and reconstructing a two-dimensional velocity field. Nevertheless, a tomogram should not be interpreted as an exact photograph of a defect: cracks can produce enlarged acoustic shadows, and irregular geometry can create incomplete paths and false positives [1,4,9]. Ultrasonic methods can offer higher spatial resolution, but attenuation increases with frequency; consequently, frequency must be balanced against penetration and signal strength [13]. Recent evidence indicates that 45-kHz ultrasonic measurements can improve defect discrimination in some urban-tree applications [15].

3.3 Acoustic tomography

Acoustic tomography is among the most established methods for internal cross-sectional assessment. Tests on black cherry demonstrated that acoustic tomography can detect heartwood decay, but decay estimates may be conservative and cracks can cause overestimation [4]. Similarly, combined visual inspection, stress-wave testing, tomography and resistance microdrilling on red oak showed that tomography was effective for locating the general defect while drilling helped distinguish decay from crack-induced acoustic shadows [3]. For irregular tropical tree trunks, careful sensor placement and piece-wise scanning can avoid incomplete chords that otherwise generate false indications [9].

Table -1: Functional comparison of major NDE approaches synthesized from the supplied literature

Method	Primary observable	Typical strength	Important limitation
Visual / TLS / photogram-metry	Geometry & surface condition	Fast screening; tree architecture	Internal defects largely invisible
Stress wave / ultrasonic	Wave velocity /	Stiffness-related and	Species, moisture

	TOF	discontinuity screening	and path effects
Acoustic tomography	2-D velocity field	Internal mapping of cross-section	Cracks/geometry can enlarge shadows
Resistance drilling	Local drilling resistance	Precise confirmation along a path	Semi-invasive; local coverage

3.4 Resistance microdrilling

Resistance drilling measures the resistance encountered by a small bit as it traverses wood. Low-resistance regions can indicate cavities or degraded wood, while periodic changes can correspond to growth-ring structure [10]. In Eucalyptus, an expert system combining IML-Resistograph traces with the CODIT concept produced a statistically significant relationship between predicted and actual decay area; the reported model for total decay area had R^2 = 0.7584 for 17 sections [10]. The same study reported that the method was comparatively inexpensive and rapid, but also noted the possibility of spreading decay organisms through drilling debris. Thus, resistance drilling is best positioned as a targeted confirmation tool rather than a universal first-line scan.

3.5 Electrical resistance tomography

ERT senses spatial variation in electrical resistance, which is influenced by moisture and ionic conditions as well as wood degradation. A comparative study of 80 trees found that ERT was more strongly associated with measured decay severity when true decay severity was below 30% (R^2 = 0.677), whereas stress-wave tomography showed the stronger relationship at decay severity ≥30% (R^2 = 0.645) [6,26]. This suggests that sensor selection may reasonably depend on the anticipated decay stage rather than assuming a single technique is optimal under all conditions. Recent work on tropical standing trees further supports ERT for identifying heartwood, sapwood and decay patterns in species such as sandalwood, red sanders and agarwood, indicating its potential value in region- and species-specific inspection programmes [24].

3.6 Ground-penetrating radar and stand-off radar

GPR is attractive because it is compact and can interrogate electromagnetic-property contrasts associated with internal features. However, conventional tree GPR requires slow contact scanning and can be difficult on small-diameter or irregular trunks. In a 147-tree, 33-species study, acoustic tomography was useful for detecting internal decay and cavities, while the tested Tree Radar Unit produced 85% false-positive predictions, illustrating the importance of field validation and careful interpretation [5]. An integrated ultrasonic-tomography/GPR full-waveform-inversion approach has more recently been proposed to improve the initial model and imaging resolution for internal decay, demonstrating the value of combining complementary sensing modalities rather than relying on GPR alone [25].

A major development is the stand-off radar scheme reported by Qian et al. The system moves an antenna along a straight trajectory without trunk contact, generates B-scans, removes air–bark and system clutter, and applies a multilevel feature-fusion neural network. The reported processing increased signal-to-clutter/noise ratio by more than 30 dB for trunk samples and 22 dB for living-tree measurements, while the classifier achieved more than 96% accuracy on fresh-cut trunk samples [16]. This is important because it shifts NDE from labor-intensive point or circumferential measurements toward rapid population-scale screening. The reported results support the use of deep-learning-assisted, contactless radar as a rapid screening layer, although validation on living trees remains necessary.

3.7 Infrared thermography

IRT is a non-contact technique that detects surface thermal radiation and converts it into a temperature map. Healthy and deteriorated tissues can produce different thermal patterns, making IRT attractive for rapid screening [7]. Its major limitation is that thermal anomalies are not defect-specific: ambient temperature, humidity, solar loading, emissivity, wind and viewing conditions can influence the measured field. Consequently, IRT is better treated as a screening layer that identifies suspicious regions for subsequent investigation rather than as a standalone structural-capacity measurement.

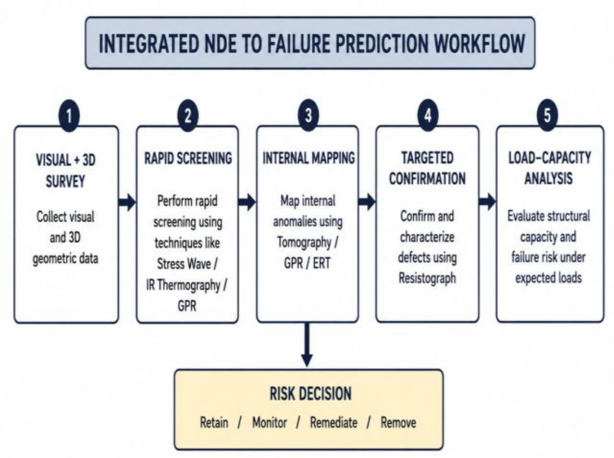

Fig - 2. Proposed staged workflow integrating rapid screening, internal characterization and mechanical risk assessment.

4. FROM DEFECT DETECTION TO FAILURE PREDICTION

NDE becomes most useful when its outputs are translated into structural demand and residual capacity. A simplified bending relation is $\sigma = Mc/I$, where M is the bending moment, c is the distance from the neutral axis to the critical fiber and I is the second moment of area. For a defective cross-section, the effective geometry and material properties are reduced, so the relevant quantity is residual capacity rather than defect area alone. The tree-statics literature emphasizes that wind load, material properties and load-bearing geometry must be considered together [12]. Pulling tests provide an empirical bridge between tree morphology and mechanical response; however, static pulling should not be assumed identical to dynamic storm loading [11]. Controlled pulling tests have also been used to estimate the critical wind speed associated with root-plate windthrow [18], reinforcing the role of mechanical validation in converting NDE observations into stability estimates.

The review evidence supports a hierarchical prediction architecture. First, geometry and visible symptoms identify likely failure zones. Second, wave, thermal and electromagnetic sensing identifies internal anomalies. Third, tomography estimates their spatial distribution. Fourth, targeted resistance drilling resolves ambiguous defect type or boundary. Finally, the measured geometry and estimated material condition are incorporated into a load–capacity model. The resulting decision variable should ideally express uncertainty, for example as a probability or safety margin, rather than as a binary 'safe/unsafe' label.

5. COMPARATIVE EVIDENCE AND INTEGRATED INTERPRETATION

Table -2. Selected quantitative and qualitative findings from the supplied studies.

Evidence / study	Main result	Implication for failure prediction
Wang et al. [2]	Stress-wave properties correlated with static bending properties; 168 standing trees	Useful for stiffness/strength screening
Wang & Allison [3]	Tomography located general defects; drilling differentiated crack/decay	Use multimodal confirmation
Liang et al. [4]	Decay detected; cracks can enlarge tomographic shadows	Defect type must be interpreted
Wu et al. [5]	Acoustic tomography useful; tested TRU had 85% false positives	GPR needs validation and geometry awareness
Yue et al. [6]	ERT stronger at early decay; stress-wave stronger at later decay	Stage-dependent sensor selection
Vidal &Pitarma [7]	IRT is rapid and non-contact but non-specific	Use as screening layer
Gilbert et al. [9]	Sonic tomography + image analysis worked on irregular trunks	Sensor geometry is critical
Johnstone et al. [10]	Resistograph expert system predicted decay area; R^2=0.7584	Targeted local confirmation is feasible
Kane & Clouston [11]	Codominant failures occurred at lower stress than stem failures	Branch unions require explicit risk assessment
Qian et al. [16]	Stand-off radar + MLFF-Net >96% accuracy on fresh-cut samples	Potential for rapid contactless screening

6. PROPOSED MULTIMODAL FAILURE-PREDICTION FRAMEWORK

Based on the reviewed evidence, an operational inspection system can be organized into five levels: (i) visual and geometric screening; (ii) rapid non-contact or low-contact sensing; (iii) cross-sectional internal imaging; (iv) targeted local confirmation; and (v) structural analysis. The framework should preserve the distinction between 'defect detection' and 'failure prediction'. A defect is an observed or inferred discontinuity; failure prediction requires estimating how that discontinuity changes structural resistance under expected loading. Recent work on branch architecture and low-cost 3-D reconstruction supports the use of quantitative tree geometry as an input to this structural stage [21,22].

A practical risk score can therefore be constructed conceptually from four normalized components: geometric demand, material degradation, defect geometry and environmental exposure. Such a score should be calibrated using field failure datasets and should not be treated as a validated numerical index until species-specific and climate-specific data are available. The key advantage of this architecture is traceability: each risk decision can be linked to a measured signal, inferred defect, structural assumption and uncertainty range.

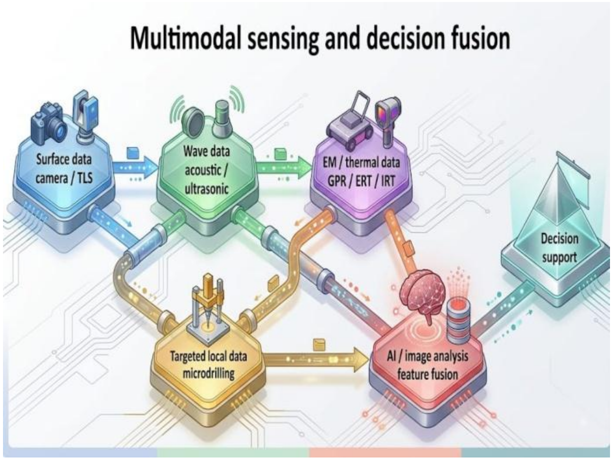

Fig - 3. Conceptual multimodal sensor-fusion architecture for tree structural-risk assessment.

7. RESEARCH GAPS AND FUTURE DIRECTIONS

The literature reveals several barriers to reliable population-scale failure prediction. First, sensor outputs are strongly affected by species, anisotropy, moisture, temperature, bark thickness and trunk geometry. Second, many techniques detect internal anomalies without directly estimating residual mechanical strength. Third, cracks and decay can produce similar signatures in acoustic methods. Fourth, training datasets for machine learning remain small and species-specific; the stand-off radar study itself notes the need for fine-tuning on living-tree data and further validation on species with irregular shapes or higher electromagnetic losses [16]. Mechanical studies likewise show that failure resistance depends on structural form and attachment characteristics, including branch-to-trunk proportions and root anchorage behaviour [19,20].

Future systems should therefore combine synchronized geometry, acoustic, electromagnetic and thermal measurements with weather and wind exposure data. Digital tree models could provide the geometric basis for bending and buckling calculations, while machine learning could perform anomaly detection and sensor-fusion rather than replace engineering interpretation. Three-dimensional LiDAR and photogrammetric reconstruction can supply the geometry needed for digital structural models [21,22], while controlled pulling and finite-element approaches provide routes for calibrating load-capacity relationships [18,19,23]. Field validation should use retained or removed trees for ground truth, with standardized reporting of false positives, false negatives, defect dimensions and uncertainty. The recent work on standardized ultrasonic velocity thresholds—35% of maximum velocity for cavity detection and 50% for cavity-plus-decay detection across 38 discs from 21 species—also illustrates the value of cross-species calibration, while acknowledging that a small accuracy loss may be acceptable for practical deployment [15].

8. CONCLUSIONS

The supplied literature demonstrates that no single NDE technique is sufficient for dependable prediction of tree-stem or branch failure. Visual and geometric sensing provide efficient screening; stress-wave and ultrasonic methods indicate changes in elastic response; acoustic tomography maps internal anomalies; ERT can be valuable in early decay; resistance drilling provides localized confirmation; IRT enables rapid thermal screening; and radar offers a promising electromagnetic pathway. Mechanical pulling and tree-statics methods are particularly important because they connect measured tree condition with load and capacity [18,19,23]. Branch-attachment strength studies further demonstrate that stem and branch architecture must be considered explicitly when failure prediction is extended from trunks to branches [20].

The most defensible direction is therefore an integrated, staged and uncertainty-aware workflow. Rapid screening should minimize unnecessary invasive testing, while targeted multimodal measurements should resolve defect type and extent. The final decision should combine defect information with tree geometry, material properties and environmental loading. Deep-learning-assisted stand-off radar is a particularly promising development for rapid contactless screening, but broader species validation and living-tree training data are still required. The long-term goal should be a digital inspection framework that converts multimodal sensor observations into transparent estimates of residual capacity and failure probability rather than relying on any single diagnostic image. The addition of low-cost 3-D reconstruction [22], ERT for tropical standing trees [24], and integrated ultrasonic/GPR imaging [25] provides further support for a multimodal architecture in which each sensor contributes a different physical observable.

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