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URBAN TREE RISK ASSESSMENT METHODS: A CRITICAL REVIEW OF VISUAL, INSTRUMENTAL, AND QUANTITATIVE APPROACHES

MÉTODOS DE AVALIAÇÃO DO RISCO DE QUEDA DE ÁRVORES URBANAS: UMA REVISÃO CRÍTICA DE ABORDAGENS VISUAIS, INSTRUMENTAIS E QUANTITATIVAS

MÉTODOS DE EVALUACIÓN DEL RIESGO DE CAÍDA DE ÁRBOLES URBANOS: UNA REVISIÓN CRÍTICA DE ENFOQUES VISUALES, INSTRUMENTALES Y CUANTITATIVOS

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ABSTRACT

Tree risk assessment is an essential activity for urban forest management, aiming to ensure public safety and mitigate material and social damages. However, numerous methods are applied in practice and the lack of consensus regarding their use render the decision-making processes complex and uncertain. In this context, this study aimed to compile and critically analyze commonly used methods for determining potential tree risk. A structured narrative literature review was conducted, based on the qualitative analysis of scientific articles addressing visual assessment methods (i.e., VTA, ISA BMP, USDA), non-destructive instrumental techniques (i.e., resistance drilling, acoustic tomography), and quantitative decision-support models (i.e., AI, expert systems). The results indicate that visual methods, although widely applied due to their practicality and low cost, are highly subjective and have limited capability to detect internal structural defects. Instrumental techniques, such as resistance drilling and acoustic tomography, enhance diagnostic reliability but present operational and economic constraints. Integrated approaches and predictive models emerge as promising alternatives to reduce uncertainty and support more consistent management decisions. It is concluded that tree risk assessment could potential benefit from the integration of multiple methods, considering technical, operational, and social aspects to achieve more reliable and effective evaluations in urban environments.

Keywords: Tree Risk Assessment. Urban Forestry. Acoustic Tomography. Resistance Drilling. Urban Tree Management.

RESUMO

A avaliação de risco de árvores é uma atividade essencial para a gestão da floresta urbana, visando garantir a segurança pública e mitigar danos materiais e sociais. No entanto, numerosos métodos são aplicados na prática e a falta de consenso quanto ao seu uso torna

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os processos de tomada de decisão complexos e incertos. Nesse contexto, este estudo teve como objetivo compilar e analisar criticamente métodos comumente utilizados para determinar o risco potencial de árvores. Uma revisão narrativa estruturada da literatura foi conduzida, baseada na análise qualitativa de artigos científicos que abordam métodos de avaliação visual (VTA, ISA BMP, USDA), técnicas instrumentais não destrutivas (perfuração por resistência, tomografia acústica) e modelos quantitativos de apoio à decisão (IA, sistemas especialistas). Os resultados indicam que os métodos visuais, embora amplamente aplicados devido à sua praticidade e baixo custo, são altamente subjetivos e apresentam capacidade limitada para detectar defeitos estruturais internos. Técnicas instrumentais, como a perfuração por resistência e a tomografia acústica, aumentam a confiabilidade do diagnóstico, mas apresentam limitações operacionais e econômicas. Abordagens integradas e modelos preditivos surgem como alternativas promissoras para reduzir a incerteza e apoiar decisões de manejo mais consistentes. Conclui-se que a avaliação de risco de árvores pode potencialmente se beneficiar da integração de múltiplos métodos, considerando aspectos técnicos, operacionais e sociais para alcançar avaliações mais confiáveis e eficazes em ambientes urbanos.

Palavras-chave: Avaliação de Risco Arbóreo. Arborização Urbana. Tomografia Acústica. Resistografia. Gestão Urbana.

RESUMEN
La evaluación del riesgo de árboles es una actividad esencial para la gestión del bosque urbano, con el objetivo de garantizar la seguridad pública y mitigar daños materiales y sociales. Sin embargo, numerosos métodos se aplican en la práctica y la falta de consenso respecto a su uso hace que los procesos de toma de decisiones sean complejos e inciertos. En este contexto, este estudio tuvo como objetivo compilar y analizar críticamente métodos comúnmente utilizados para determinar el riesgo potencial de árboles. Se llevó a cabo una revisión narrativa estructurada de la literatura, basada en el análisis cualitativo de artículos científicos que abordan métodos de evaluación visual (VTA, ISA BMP, USDA), técnicas instrumentales no destructivas (perforación por resistencia, tomografía acústica) y modelos cuantitativos de apoyo a la toma de decisiones (IA, sistemas expertos). Los resultados indican que los métodos visuales, aunque ampliamente aplicados debido a su practicidad y bajo costo, son altamente subjetivos y tienen una capacidad limitada para detectar defectos estructurales internos. Las técnicas instrumentales, como la perforación por resistencia y la tomografía acústica, mejoran la confiabilidad del diagnóstico, pero presentan limitaciones operativas y económicas. Los enfoques integrados y los modelos predictivos surgen como alternativas prometedoras para reducir la incertidumbre y apoyar decisiones de gestión más consistentes. Se concluye que la evaluación del riesgo de árboles podría beneficiarse potencialmente de la integración de múltiples métodos, considerando aspectos técnicos, operativos y sociales para lograr evaluaciones más confiables y efectivas en entornos urbanos.

Palabras clave: Evaluación del Riesgo Arbóreo. Arboricultura Urbana. Tomografía Acústica. Resistografía. Gestión Urbana.

1 INTRODUCTION

Urban trees play a fundamental role in promoting environmental quality and human well-being in cities, contributing to the mitigation of urban heat islands, carbon sequestration, reduction of surface runoff, and the aesthetic and social enhancement of urban spaces (Oliveira et al., 2026; Sun; Wu; Li, 2024; Wolf et al., 2020)However, these benefits coexist with potential risks associated with the structural failure of trees or their components, particularly in highly urbanized environments, where the constant presence of human and infrastructural targets amplifies the consequences of potential failures (Judice et al., 2021; Li et al., 2022).

Tree fall risk is traditionally defined as the combination of the likelihood of structural failure, the probability of impacting a a target, and the severity of the consequences of such impact. This approach, widely adopted in international standards and protocols, recognizes that the mere presence of structural defects does not necessarily imply high risk, making it essential to consider the spatial, social, and functional context in which the tree is located (Klein et al., 2019; Judice et al., 2021).

In urban environments, trees are subjected to adverse growing conditions, such as soil compaction, restricted rooting volume, recurrent anthropogenic interventions (e.g., pruning, construction damage), and increased exposure to extreme climatic events (e.g., hurricanes, fires (ADD CITATIONS). Some of these factors can accelerate internal degradation processes, including cavity formation and wood decay, thereby increasing susceptibility to structural failure, particularly in large and mature trees (Li et al., 2022; Okun et al., 2023).

Historically, tree risk assessment has been predominantly based on visual cues and qualitative methods, systematized through widely disseminated protocols such as those proposed by the International Society of Arboriculture (ISA) Tree Risk Assessment BMPs (Smiley, et al. 2025) and the United States Department of Agriculture (USDA) (Pokorny, 2003). The main advantages of these methods are their ease of application and low operational cost, which explains their widespread use by public managers and urban forestry professionals (Koeser et al., 2014).

However, the literature indicates that such approaches are highly dependent on the assessor's previous experience and industry accredidation, and assessments have the potential to be subjectivite (Klein et al., 2021; Koeser et al., 2016; Koeser; Smiley, 2017).

Recent studies have shown that significant divergences may occur even among experienced and certified assessors, particularly when evaluations rely exclusively on visual inspections or on limited information regarding the internal condition of the trunk. Okun et al. (2023) demonstrated that the progressive incorporation of information obtained through instrumental techniques, such as resistance drilling and acoustic tomography, can substantially alter the classification of failure likelihood assigned by arborists, reinforcing the existence of inherent uncertainties in the risk assessment process and the need for more objective approaches (Okun et al., 2023).

In this context, there has been growing interest in integrating non-destructive instrumental methods into tree risk assessment in order to improve the detection of internal defects and reduce uncertainty associated with management decisions. Techniques such as acoustic tomography, resistance drilling, and controlled pulling tests have been widely investigated, showing potential to provide measurable physical parameters related to the structural integrity of trees (Li et al., 2022; Okun et al., 2023).

In parallel, recent advances point to the use of quantitative models and artificial intelligence techniques as promising tools for tree risk assessment. The application of machine learning algorithms has demonstrated the ability to reduce the complexity of traditional protocols by identifying subsets of critical variables capable of classifying risk with satisfactory levels of accuracy, while also supporting faster and more standardized decision-making processes in the context of urban management (Maria et al., 2023).

Despite these advances, there is still no consensus in the literature regarding the most appropriate way to integrate visual, instrumental, and quantitative methods into a robust and operational tree fall risk assessment model. In addition, social aspects, such as community risk perception and urban governance processes, exert a direct influence on management decisions, reinforcing the need for approaches that simultaneously consider technical, social, and institutional criteria (Judice et al., 2021).

Given this scenario, the importance of critical reviews that systematize existing methods, discuss their limitations and potentialities, and identify knowledge gaps capable of guiding the development of more integrated and reliable models for assessing tree risk in urban environments becomes evident.

2 THEORETICAL FRAMEWORK

2.1 CONCEPT OF RISK APPLIED TO URBAN TREES

Treerisk assessment in urban environments is a complex process that involves the integrated analysis of the likelihood of structural failure, the probability of impact on a target, and the severity of the consequences associated with such impact. This approach recognizes that risk is not an intrinsic property of the tree, but rather results from the interaction between its structural condition, the built environment, and human presence.

Thus, a tree with major structural defects may not represent high risk in the absence of potential targets, whereas apparently healthy individuals with less obvious defects (e.g., extensive internal decay, severe root damage) may pose significant risk when located in highly occupied areas.

Several studies indicate that tree risk assessment is strongly influenced by human factors, particularly the assessor's perception, level of experience, and the protocol adopted (Bindewald; Michiels; Bauhus, 2020). Even when standardized methods are applied, significant variability may occur among assessors, directly affecting risk classifications and management recommendations. Koeser and Smiley (2017) demonstrated that assessor influence is particularly relevant for components related to the probability of impact and the consequences of failure, reinforcing the subjective nature inherent to qualitative risk assessments (Koeser; Smiley, 2017).

In addition, studies on social perception indicate that the concept of risk extends beyond the technical dimension and is also shaped by cultural, social, and institutional factors (Slovic, 1987). Public acceptance of management decisions, such as heavy pruning or tree removal, depends not only on technical risk assessment but also on how risk is communicated and perceived by the community (Judice et al., 2021).

These aspects reinforce the need for more transparent, reproducible, and technically grounded risk assessment methods.

2.2 STRUCTURAL FAILURES AND MANAGEMENT EFFECTS IN URBAN TREES

Structural failures in urban trees are associated with a combination of biological, mechanical, and anthropogenic factors, including biodeterioration processes, asymmetric growth, restrictions on root development, soil compaction, and inadequate management practices. Among the main failure mechanisms are stem breakage, root system collapse, and failure of structural branches, often intensified by the presence of internal decay that is not externally visible.

Management practices, particularly heavy pruning, have been widely discussed in the literature as factors that may compromise the structural integrity of trees, especially when a laod is applied (i.e., wind, snow, ice). Suchocka et al. (2021) demonstrated that intensive interventions can generate extensive wounds, facilitate colonization by wood-decaying fungi, and accelerate wood degradation processes, resulting in increased risk of structural failure over time, even when an initial compensatory physiological response occurs (Suchocka et al., 2021).

The difficulty in detecting these internal deterioration processes at an early stage represents one of the main challenges in urban arboriculture. Internal defects may develop over long periods without evident external manifestations, making reliance exclusively on visual inspections insufficient for tree fall risk assessment.

2.3 VISUAL METHODS FOR TREE FALL RISK ASSESSMENT

Visual methods constitute the historical foundation of tree risk assessment and continue to be widely used due to their practicality, rapid application, and low operational cost. These methods are formalized in different protocols and forms, such as those proposed by the International Society of Arboriculture (ISA) Tree risk Assessment BMPs (Smiley et al., 2025), the USDA Forest Service (Pokorny, 2003), and approaches such as Visual Tree Assessment (VTA) (Fink, 2009).

Despite their widespread adoption, comparative studies have demonstrated significant limitations associated with visual methods, mainly related to subjectivity and low reproducibility. Coelho-Duarte et al. (2021), when analyzing six visual methods applied to the same set of trees, observed statistically significant differences in risk ratings, both among methods and among assessors, for virtually all risk components (Coelho-Duarte et al., 2021).

The depth of visual assessment also directly influences the results obtained. Koeser et al. demonstrated that limited visual assessments tend to underestimate the likelihood of failure when compared to basic and advanced assessments, although increasing the level of detail does not completely eliminate variability among assessors (Koeser et al., 2017).

These findings indicate that, although useful as initial screening tools, visual methods present important limitations in the identification of internal defects and in the objective quantification of risk.

2.4 NON DESTRUCTIVE INSTRUMENTAL METHODS

The development of non-destructive instrumental methods has represented a significant advance in tree risk assessment, particularly with regard to the detection of internal defects that cannot be identified through visual inspections. Among these techniques, resistance drilling and acoustic tomography stand out as being widely investigated in the scientific literature (Cristini et al., 2022; Jang et al., 2025; Lee; Son, 2024; Liu; Li, 2018; Paulić et al., 2022; Wu et al., 2018)

Resistance drilling is based on measuring the resistance offered by the wood to the penetration of a small-diameter needle, with the resulting signal being strongly correlated with wood density along the drilling path. Rinn (2015) emphasizes that the correct interpretation of resistance drilling profiles requires detailed knowledge of wood anatomy, since natural variations between earlywood and latewood may be mistakenly interpreted as structural defects.

In addition, relatively small losses in density may result in expressive reductions in mechanical strength, making resistance drilling particularly relevant for the detection of incipient decay.

Acoustic tomography, in turn, is based on measuring the propagation time of sound waves between sensors distributed around the trunk, generating two-dimensional maps of velocity distribution in the cross-sectional plane. Although widely used, this technique traditionally assumes straight-line wave propagation paths, an assumption that may not adequately reflect the structural heterogeneity of wood. Li and Liu (2018) proposed a hybrid propagation model combining straight and curved paths, demonstrating significant improvements in tomographic image accuracy and a reduction of artifacts.

Comparative studies indicate that both resistance drilling and acoustic tomography show good correspondence with destructive reference methods, such as computed tomography and visual analysis of cross-sections. Reinprecht and Šupina observed high agreement between these techniques in identifying severely deteriorated zones, although limitations persist in the detection of early stages of decay (Reinprecht; Šupina, 2015).

Similar results were reported by Tarmu et al., who demonstrated that acoustic tomography significantly outperforms visual assessment, but shows low sensitivity to incipient defects (Tarmu et al., 2022).

In addition to technical limitations, operational aspects influence the adoption of these methods in practice. Baláš et al. (2020) highlight that the application of tomography is relatively costly and time-consuming, making it more suitable as a complementary tool in situations of uncertainty or high potential risk rather than as a large-scale screening method (Baláš; Gallo; Kuneš, 2020).

2.5 INTEGRATION OF METHODS, QUANTITATIVE MODELS, AND DECISION SUPPORT

Recent literature points to the need to integrate visual, instrumental, and quantitative approaches as a strategy to reduce uncertainty associated with tree risk assessment (He; Wei; Wang, 2024; Papandrea et al., 2022). Studies demonstrate that the isolated use of any single method presents limitations, whereas the combination of different techniques allows a more comprehensive understanding of tree structural condition (Emerick; Martini; De Souza, 2025)

In this context, quantitative models and expert systems have been proposed as promising tools to support decision-making. The application of regression-based models, decision trees, and artificial intelligence has shown potential to reduce dependence on human subjectivity, identify subsets of critical variables, and optimize extensive and poorly operational protocols (Maria et al., 2023; Vitkus et al., 2020).

The integration of data derived from instrumental methods, such as acoustic tomography and resistance drilling, into predictive models represents an emerging trend in the literature, with potential to increase the reliability of assessments and provide more robust support for management decisions in urban forestry. However, there is still a lack of studies validating these models under real field conditions, reinforcing the need for research that correlates measurable physical parameters with indicators of structural failure and effective risk.

3 METHODOLOGY

This study is based on a narrative and analytical literature review aimed at compiling and critically discussing the main methods for assessing tree risk described in the scientific literature. The adopted approach allowed the integration of different theoretical and technical perspectives, encompassing visual inspection methods, non-destructive instrumental techniques, and quantitative decision-support approaches widely used in the context of urban forestry.

The development of the theoretical framework and discussion was based on the review of scientific articles published in indexed journals, as well as technical documents and guidelines widely recognized in professional practice. The sources were identified through searches in consolidated scientific databases and by selecting relevant studies that directly addressed tree risk assessment or structural failure in living trees, prioritizing publications in English and Portuguese.

The selected studies were analyzed qualitatively, considering their objectives, methodological principles, and main contributions. For purposes of organization and discussion, the methods described in the literature were grouped into thematic categories, including visual approaches, non-destructive instrumental techniques, and integrated risk assessment models. The analysis focused on conceptual comparisons among methods, highlighting advantages, limitations, degree of subjectivity, practical applicability, and potential for integration between different approaches.

As this study is based exclusively on information available in the literature, there was no direct involvement of human subjects, animals, or sensitive data, and submission to a research ethics committee was not required. It is acknowledged that the diversity of methods, application contexts, and criteria adopted in the analyzed studies may limit direct comparisons and quantitative generalizations. Nevertheless, the adopted approach provides a concise and critical overview of the current state of knowledge, contributing to a better understanding of the potentialities and limitations of tree fall risk assessment methods.

4 RESULTS AND DISCUSSION

The critical analysis of the literature indicates that the main limitation of the methods currently employed in tree risk assessment lies not only in their technical foundations, but also in the way these methods are applied and interpreted in real urban management contexts. Although significant advances have been observed in recent decades, particularly with the incorporation of non-destructive instrumental techniques, risk assessment remains strongly dependent on qualitative judgments and context-based decisions.

With regard to visual methods, the analyzed studies demonstrate that the variability observed among protocols and assessors is not a secondary side effect, but rather a structural characteristic of these approaches. Divergences in risk classifications, widely documented by Koeser and Smiley (2017), Koeser et al. (2017), and Coelho-Duarte et al. (2021), arise from the fact that fundamental risk components—such as the probability of impact and the severity of consequences—are not objectively measurable and rely heavily on assessor interpretation. This finding has direct implications for urban management, as different decisions may be made for the same tree, even when assessments are conducted by experienced professionals using recognized protocols.

Practical application studies further reinforce this conceptual limitation. In extensive environments, such as university campuses or public squares, the adoption of visual methods has proven to be operationally efficient but technically limited, particularly for large trees or those protected by specific legislation (Ivasko Júnior et al., 2019; Kholis et al., 2019). In such contexts, visual assessment tends to prioritize evident external defects, while internal deterioration processes remain underestimated, increasing uncertainty associated with the actual risk of failure.

The incorporation of non-destructive instrumental methods represents, in this scenario, a relevant but not definitive advance. Resistance drilling and acoustic tomography have demonstrated superior capability for identifying and characterizing internal defects when compared to visual inspections, especially at moderate to advanced stages of deterioration (Reinprecht et al., 2015; Rinn, 2015; Tarmu et al., 2022). However, the literature consistently points out that these techniques present limitations both in detecting

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incipient decay and in directly interpreting structural failure risk, since they provide physical information that still needs to be translated into management decisions.

In addition, operational and economic aspects restrict the indiscriminate application of these techniques. The time required to perform instrumental tests and the associated costs make their use impractical in large-scale inventories, reinforcing the need for hierarchical assessment strategies (Baláš; Gallo; Kuneš, 2020). Consequently, instrumental methods tend to be more effective when employed as confirmation tools or for diagnostic refinement, rather than as direct substitutes for visual assessments.

In this context, recent discussions in the literature on the integration of methods as the most consistent approach for tree risk assessment (Lin et al., 2016; Van Wassenaer; Richardson, 2009). The combination of visual inspections, instrumental data, and quantitative models allows for a reduction in uncertainty associated with management decisions, while balancing operational feasibility and technical reliability (Ataide et al., 2023; Linhares et al., 2021) Studies exploring predictive models, expert systems, and artificial intelligence techniques suggest that integrating multiple variables may contribute to the standardization of assessments and to reducing the subjectivity inherent in decision-making processes (Vitkus et al., 2020; Maria et al., 2023).

Nevertheless, the literature still lacks models that are broadly validated under real field conditions and capable of correlating measurable physical parameters—such as density loss or variations in acoustic velocity—with actual probabilities of failure and potential consequences. This gap indicates that the current challenge is not only technological, but also conceptual: transforming diagnostic information into reliable risk estimates that can support transparent, reproducible, and socially acceptable decisions.

Overall, the discussed results indicate that tree risk assessment should be understood as an adaptive process in which different methods play complementary roles (Table 1). The selection of tools should consider not only technical accuracy, but also the urban context, available resources, target exposure, and the social and legal implications associated with management decisions. This integrated perspective representes potential pathway for advancing tree risk assessment practices in urban forestry.

Table 1

Comparative synthesis of the main methods for tree fall risk assessment

CATEGORY	METHOD	MAIN ADVANTAGES	MAIN LIMITATIONS
Visual	VTA / ISA / USF / Sampaio	Fast application, low cost, applicable on a large scale, suitable for initial screening	High subjectivity, strong assessor influence, low detection of internal defects

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Instrumental	Resistance drilling	High sensitivity to density variation, effective for identifying internal decay	Operator-dependent interpretation, point-based assessment
Instrumental	Acoustic tomography (PiCUS)	Spatial visualization of internal defects, higher accuracy than visual methods	High cost, longer application time, low sensitivity to incipient decay
Integrated	Visual assessment + instrumental methods	Reduced uncertainty, higher diagnostic reliability	Greater operational complexity and cost
Emerging	Quantitative models / AI / expert systems	Reduced subjectivity, integration of multiple variables, decision support	Need for field validation, dependence on high-quality data

Source: Prepared by authors.

5 CONCLUSION

The critical analysis of the literature indicates that tree risk assessment in urban environments remains characterized by a high degree of uncertainty, resulting both from the biological and structural complexity of trees and from the inherent limitations of the available methods. Visual approaches, although indispensable for initial screening and widely used due to their operational feasibility, are highly dependent on the assessor and have limited capacity to detect internal defects. Non-destructive instrumental methods, such as resistance drilling and acoustic tomography, significantly enhance structural diagnosis, but do not fully eliminate subjectivity nor allow, on their own, the direct quantification of failure risk, particularly at early stages of deterioration.

In this context, the literature converges toward the adoption of integrated assessment strategies, in which visual methods, instrumental techniques, and quantitative models operate in a complementary manner. The integration of these approaches represents the most promising pathway to reduce uncertainty, increase transparency in management decisions, and align technical assessments with the operational, social, and legal requirements of urban tree management. Future advances depend on the development and validation of models capable of correlating measurable physical parameters with actual probabilities of failure and potential consequences, thereby contributing to more objective, reproducible, and field-applicable assessments.

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