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ANALYSIS OF ANATOMIC STRUCTURES OF TREES IN RELATION TO UPROOTING BEHAVIOUR: THE CASE STUDY OF *PINUS PINEA*

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ABSTRACT
Tree stability is the result of the interaction between trees and the environment around them. Therefore, morphological and anatomical features of each species significantly determine, in different ways, the stability of each individual.
Epidemiological studies of tree species in urban areas have demonstrated that trees belonging to different species exhibit different behavior of failure. The genus *Pinus*, particularly *Pinus pinea*, possesses a typical mode of uprooting, even in absence of structural defects.
Morphophysiological analysis of *Pinus pinea* provides an explanation to this peculiar mode of failure, allowing also to design a model of the mechanic, static and dynamic behavior, which is attributable, up to now, only to *Pinus pinea*.
The study of the anatomic structures of trees through morphophyisiological analysis, different among species, is therefore fundamental for a more complete and correct tree stability assessment, aiming to better prevent tree failures and with a greater accuracy.

Keywords: *Pinus pinea*, uprooting behavior, morphopysiological analysis, tree failure, tree stability.

RÉSUMÉ
La stabilité des arbres est le résultat de l'interaction entre chaque individu et son environnement.
Par conséquent, les caractéristiques morphologiques et anatomiques des differentes espèces déterminent fortement, et d'une façon différente, la stabilité de chaque arbre.
Des études épidemiologiques conduits au milieu urbain ont démontré que des arbres d'espéces différents montrent des types de ruptures structurelles specifiques. The genus *Pinus*, et *Pinus pinea* en particulier, montre un propre modèle de deracinement, même en absence de défauts structurels.
L'analyse morphophysiologique du *Pinus pinea* explique ce particulière modalitè de deracinement, permettant de revenir à un modèle de comportement mécanique, statique and dynamique, pour l'instant uniquement attribuable à cette espèce.
L'étude approfondi de l'organization anatomique de chaque individu enrichi par l'analyse morphophyisiologique, toujour différente pour les différentes espèces, devient essentiel pour une évaluation plus complète et précise de la stabilité des arbres, soit dans le diagnostic visuel que par l'utilisation d'instruments specifiques, dans le but de toujours prévenir avec une plus grande précision les ruptures et les chutes dels arbres.

Mots-clés : *Pinus pinea*, deracinement, analyse morphopysiologique, rupture, stabilité des arbres.

INTRODUCTION

The assessment of tree stability is currently applied in urban environments as a diagnostic tool to control and reduce tree failures. Based on the application of specific diagnostic protocols, the assessment of tree stability provides a phase of visual analysis that may be integrated successively by instrumental follow-up inpections. Beyond the differences in methodology, the phases of stability evaluation are geared to the identification of any qualitative or quantitative deviation from a theoretical model of an ideal tree. Such deviations, which assign a negative value because they are considered potentially able to increase the propensity to failure, are commonly referred to as defects (Morelli G., 2010; Morelli G., 2015). The recognition and measurement of these defects are then related to an estimated traditional mechanical model of trees, which presupposes the presence of some standard features such as anatomic solidarity and strict relationship between primary branches, main trunk and superficial (fasciculated) anchoring roots (Fig. 1). This strict relationship between the three different anatomic structures is guaranteed by the presence of specific anatomical features located both at the crown level (stipes) and at the base of the tree such as buttresses (Albrecht *et al.*, 1995; James K., 2003). The main trunk, at least within certain limits, can be hollow (Wessoly L., 1995). Similarly, the taproot may be completely absent without compromising the stability of the traditional mechanical behaviour (Morelli G., 2015).

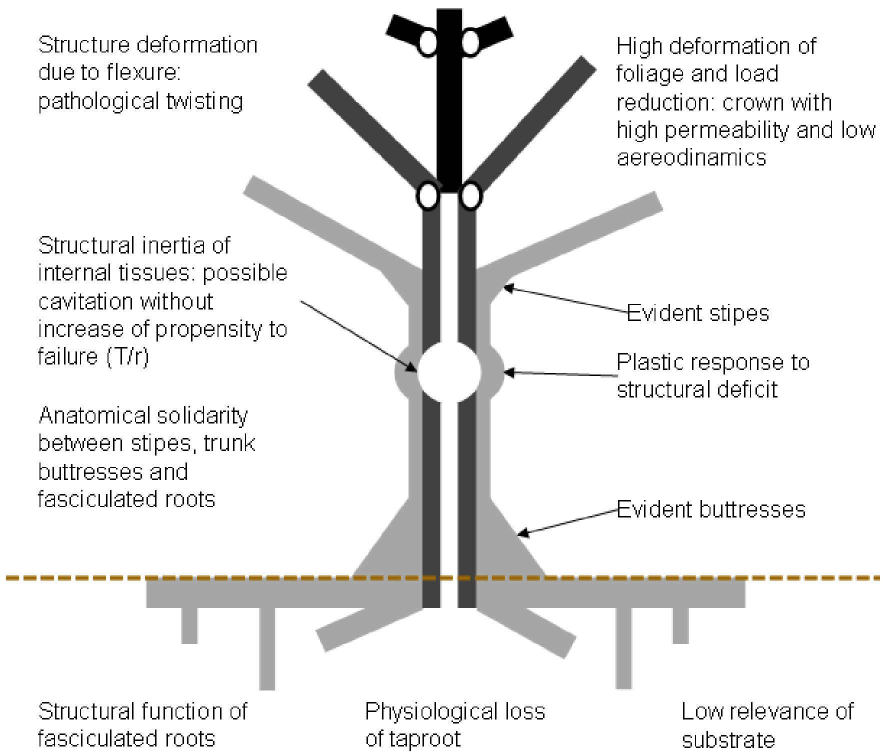
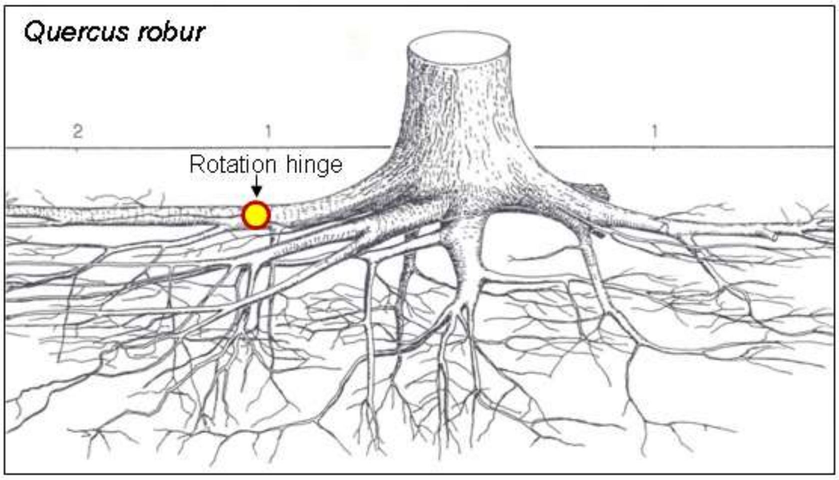


Figure 1 : Traditional mechanical model of trees (broad-leaved trees, *Cupressaceae*).
Figure 1 : Modèle mécanique traditionnel des arbres (feuillus, *Cupressaceae*).

When a tree belonging to the model described in figure 1 fails for uprooting, a rotation of the entire tree structure around a hinge of rotation occur (Fig. 2). Particularly, the rotation hinge is placed outside the projection of the main trunk to the ground (Vogel S., 1992) at a distance equal to approximately 2.5 times the diameter of the trunk measured at one meter height. After failing the tree is lying with the base raised up from the ground, resting on the root ball which is often of limited dimensions (Morelli G. and Raimbault P., 2011).



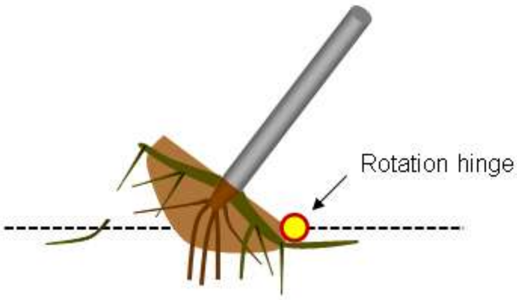


Figure 2 : Root system of traditional mechanical model of trees (broad-leaved trees, *Cupressaceae*) and individuation of the rotation hinge in case of failure (Morelli G., Raimbault P., 2011).

Figure 2 : Système racinaire du modèle mécanique traditionnel des arbres (arbres à feuilles larges, *Cupressaceae*) et individuation de la charnière de rotation en cas de chute (Morelli G., Raimbault P., 2011).

This traditional vision of the tree is characteristic of many species of hardwood and softwood and tree stability assessment, conducted either with a visual or instrumental analysis, is based on these empirical assumptions. However, even the most rigorous, systematic and professional adoption of tree stability assessment procedures does not allow to completely avoid the danger of structural failure of trees in urban areas. It is clear that there are situations, e.g. regarding to particular tree species or specific stages of life of a tree, in which the application of the most common diagnostic protocols referring to the theoretical mechanical model described above, appears to be completely ineffective.

In particular, the limits of tree stability assessment become much clearer in situations where a high frequency of particular tree species is present, as in the case of many Italian coastal cities having a common presence of *Pinus pinea*. In fact, the professional experiences about *Pinus pinea* stability assessement conducted in recent years have shown how the application of the traditional mechanical model described above is not able to significantly reduce failures for this particular species.

Therefore in this study we observed the modes of structural failure due to uprooting and we studied the anatomical structure of *Pinus pinea*. The anatomical organization of main branches, trunk and base of *Pinus pinea* higlights a specific mechanical model significantly different from the traditional one, broadly used to make assumption about tree stability assessment. The understanding of the specific mechanical model for *Pinus pinea* associated to specific stability assessment procedures is fundamental to support the understanding of structural defects with more accuracy and to ensure the stability of *Pinus pinea*.

MATERIALS AND METHODS

From year 2013 to year 2016 we have been recorded and qualitatively described the structural failure for uprooting of *Pinus pinea* occurred in the cities of Riccione (RN, Emilia-Romagna, Italy) and Cervia (RA, Emilia-Romagna, Italy). For both cities trees were rooted in sandy soil. The analysis of failures were then related to anatomical features of *Pinus pinea* to verify their compliance to a mechanical model capable of explaining the dynamics and mode of failure. We then proceeded to the comparison between this new model and the traditional one.

RESULTS

Structural failure for uprooting in *Pinus pinea*

In most of the observed cases (about 80%) failures involved adults *Pinus pinea* showing some common characteristics: evident sinking of the base of the trunk in the compressed position respect to the fall direction, moderate lifting of the base of the trunk in the opposite direction, scarce or non evident presence of pulling roots, absence of degenerative processes of the woody tissues at the base of the trunk and of the lower third of the trunk (Fig. 3). Morover, failures of *Pinus Pinea* were widely spread and a weak correlation between failures and intense metereological events (strong wind, rainfall) was found. Apparently, a generalized absence of warning symptoms and defects was reported.

Figure 3 : Stump of *Pinus pinea* after failure with evident sinking of the base of the trunk in the compressed position compared to the fall direction.
Figure 3 : Souche de *Pinus pinea*, après l'évident effondrement de la base du tronc dans la position en compression par rapport à la direction de chute.

The described uprooting behaviour assumes a rotation of the entire tree structure around a rotation hinge which is typically placed in the center of the projection of the main trunk below the ground, potentially corresponding to the taproot (Fig. 4; Vogel S., 1992). Therefore, this peculiar mode of failure is not compatible with the traditional tree mechanical model as described previously in figure

1. Particularly, it is evident that the position of the rotation hinge for *Pinus pinea* is incompatible with a strict anatomical continuity between the main trunk and the superficial (fasciculated) anchoring roots.

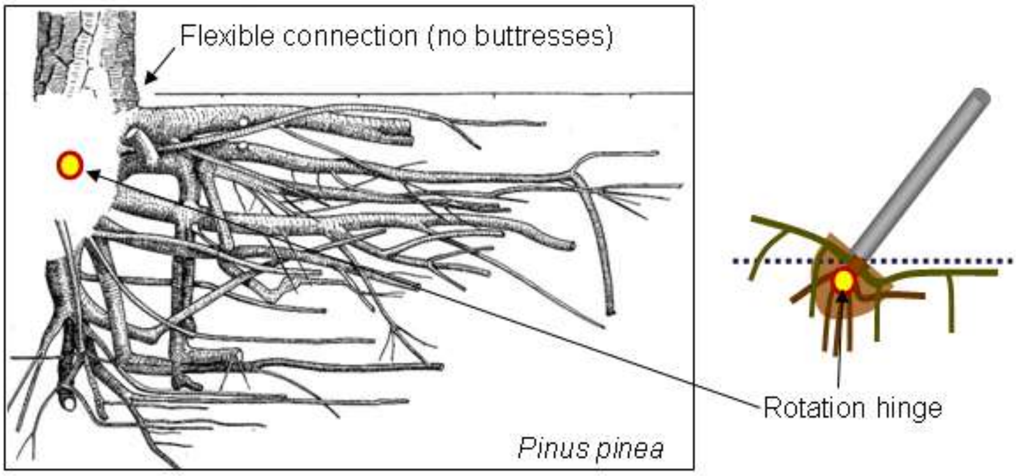


Figure 4 : Root system of *Pinus pinea* and individuation of the rotation hinge in case of failure (Morelli G., Raimbault P., 2011).
Figure 4 : Système racinaire de *Pinus pinea* et individuation de la charnière de rotation en cas de chute (Morelli G., Raimbault P., 2011).

DISCUSSION

A mechanical model for *Pinus pinea*
The qualitative examination of structural failure for uprooting of *Pinus pinea* supposes that this species is related to a mechanical model significantly different (almost opposite) from the traditional one (Fig. 5).
At least in theory, this alternative mechanical model presumes anatomical solidarity between primary branches and main trunk but, on the other hand, an elastic and flexible relationship between the trunk and the superficial fasciculated roots. This flexibility is guaranteed by the absence of specific anatomical structures of connection, such as buttresses, resulting in simple and straightforward insertion of superficial roots at the base of the trunk. Presumibly, a direct continuity between the main trunk and the taproot is present. The main trunk, therefore, can not be hollow and the taproot emerges as a fundamental element for the functioning of the mechanical model of *Pinus Pinea*.
It is noteworthy, in fact, how the insertion to the ground of *Pinus pinea* often appears completely linear and as, statistically, in the stability assessment campaigns conducted also with the help of appropriate technical instruments, it is very uncommon to detect the presence of internal cavities at the base of the trunk (Costello L.R. *et al.*, 2015).

Comparison between mechanical model of *Pinus pinea* and traditional mechanical model
The mechanical model of *Pinus pinea* suggests how the anatomical organization in this species can be considered as an adaptation to primitive type of soils, incoherent and well ventilated even in depth, in which the tree, due to the anatomical continuity between the trunk and the taproot, would fix as a pole (Morelli G. and Raimbault P., 2011). The superficial roots (fasciculated roots), with their flexible connection to the base of the trunk would avoid the extraction of the taproot in traction position, while also avoiding the sinking of the base of the trunk in the compressed position, respect to the falling direction (Morelli G. and Raimbault P., 2011). The mode of failure of *Pinus pinea* in

urban conditions are thus the expression of this specific mechanical model, exposed to anatomical changes of various origins and nature, such as the loss of the taproot or cutting of superficial fasciculated roots (Raimbault P., 1996; Morelli G. and Raimbault P., 2011).
In contrast, the traditional mechanical model suggests how other species of trees such as *Cupressaceae* and broad-leaved are better adapted to it, due to more complex and evoluted soils, consistent, sometimes compact and potentially well-drained but only in the surface (Morelli G. and Raimbault P., 2011). In this case the trees would be standing on the ground thanks to a large pedestal, consisting of superficial anchoring roots strictly connected to the main trunk through buttresses.

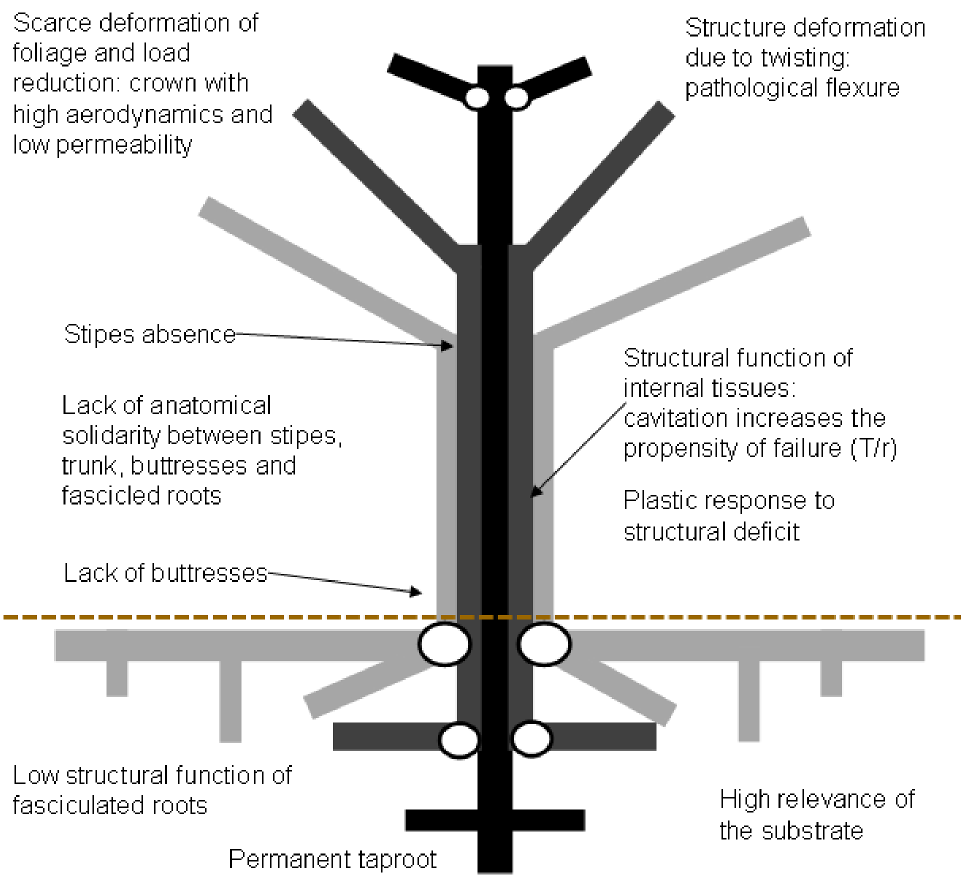


Figure 5: Mechanical model of *Pinus pinea*.
Figure 5: Modèle mécanique de *Pinus pinea*.

Morphophysiological implications of the mechanical model of *Pinus pinea*
Every mechanical model can be confirmed in the process of morphophysiological evolution. In fact, citing the well known schematization of morphophysiological stages given by P. Raimbault (Raimbault P. and Tanguy M., 1993; Raimbault P., 1994) it is known how in the plastic modification process of trees there is a correspondence between the development of the aerial part of Stage 8 (Fig.6A) and the development of the root system shown in figure 6B at Stage G, underground (Raimbault P., 1991). This correspondence set in relation the decreasing photosynthetic capacity of the tree with the deactivation of the taproot that, over time, tends to disappear replaced by the fasciculated superficial roots (Raimbault P., 1991). Trees easely able to come to the Stadium 8 / G are therefore implicitly attributable to the traditional mechanical model of figure 1.

In the case of *Pinus pinea*, however, the permanence of the taproot justifies a halt in the morphophysiological evolution upon reaching maturity. Therefore *Pinus pinea* remains indefinitely at the Stadium 7 / F (Fig. 6B and 6C) and can not be linked to the traditional mechanical model of figure 1 (Morelli G. and Raimbault P., 2011). *Pinus pinea* needs to be analyzed following a different mechanical model that can justify its shape, architecture and mode of failure (Fig. 5)
These considerations suggest that the belonging of a tree species to a specific mechanical model depends certainly on the species itself and the degree of individual morphophysiological evolution.

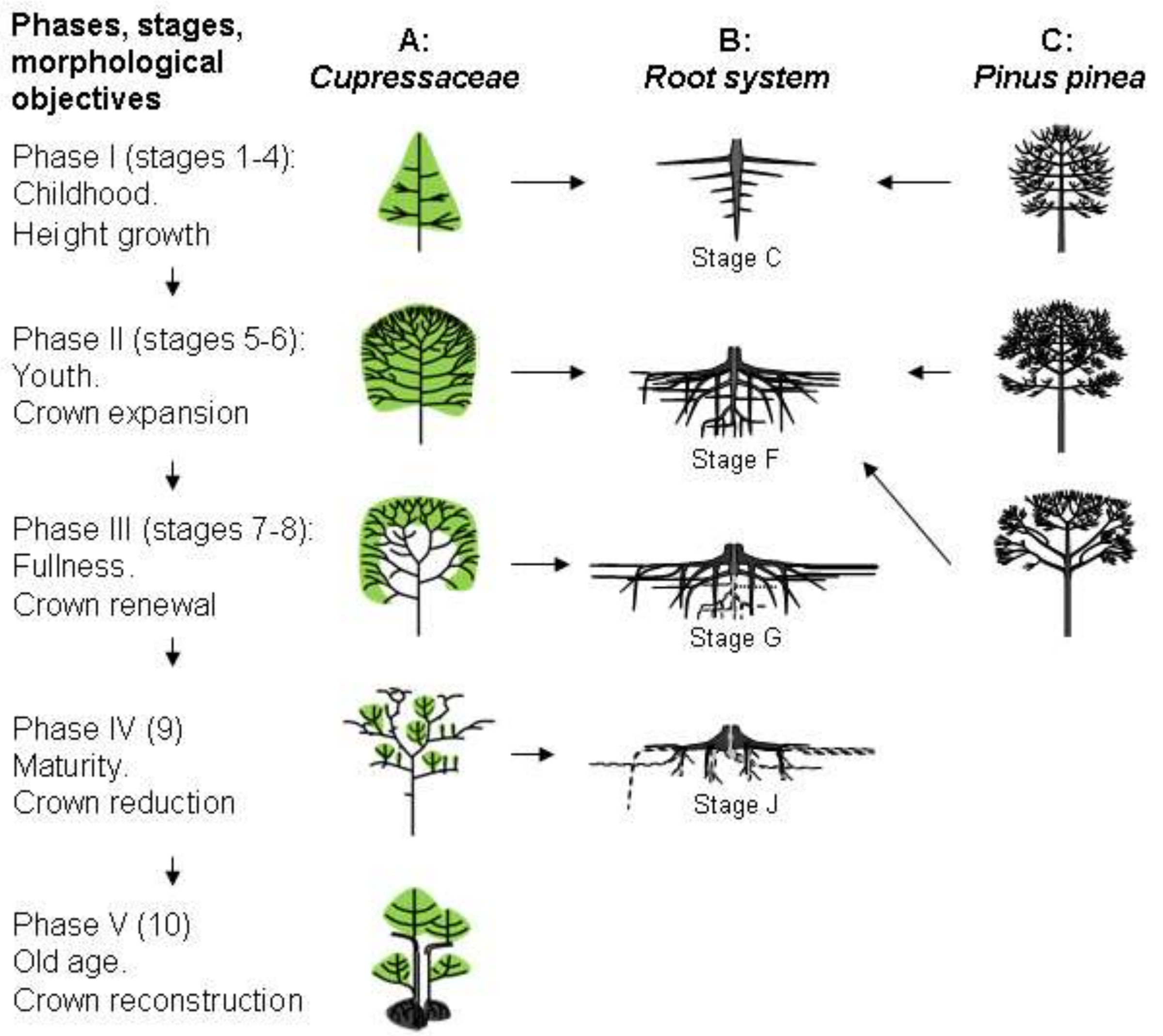


Figure 6 : Morphophysiological stages of development given by P. Raimbault for *Cupressaceae* (A) and *Pinus pinea* (C) in relation to the root system (B).
Figure 6 : Stades de développement morphophysiologique chez les *Cupressaceae* (A) et chez *Pinus pinea* (C) en relation avece le système racinaire (B), (P. Raimbault).

CONCLUSION
The anatomical analysis of the organization of *Pinus pinea* in relation to its uprooting behaviour allows to define the limits of today's most common diagnostic protocols used for tree stability assessment, establishing how important is to relate trees to the most appropriate mechanical model. Future studies will determine whether there are other mechanical models in addition to those considered and if, as it is likely, there are species that are placed in an intermediate position between these pre-defined templates.

Secondly, it seems plausible to say that the mechanical model itself represents a transient tree condition due to its natural morphophysiological evolution, meaning that particular species may adhere to different mechanical models in the course of life. Therefore, morphophysiological analysis becomes a fundamental tool in tree stability assessment.

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