



## BIOMECHANICAL OSCILLATION IN TREES: UNDERSTANDING WIND-INDUCED MOVEMENT DYNAMICS — A SYSTEMATIC REVIEW

CHANDRASEKHAR BHOI<sup>1\*</sup> and JAYANTI PRADHAN<sup>2</sup>

<sup>1</sup>Buxi Jagabandhu Bidyadhar Autonomous College, Bhubaneswar, India

<sup>2</sup>Nabakrushna Choudhury College of Teacher Education, Angul, India

\*Corresponding Author's Email- [cbhoi7918@gmail.com](mailto:cbhoi7918@gmail.com)

Wind-induced biomechanical oscillation is a critical component of tree–environment interactions, influencing mechanical stability, growth dynamics, ecological function, and long-term survival. This systematic review integrates historical, contemporary, and emerging research on how trees respond mechanically to wind through oscillation, damping, and adaptive structural modifications. Studies from biomechanics, aerodynamics, forestry engineering, and ecological modelling are synthesized to provide a comprehensive understanding of oscillation dynamics across scales. The review further presents standardized methodological approaches, summarizes current findings, identifies key limitations, and highlights future research priorities, particularly in the context of climate-change-driven extreme weather events. The insights gained have direct implications for urban forestry management, storm-risk mitigation, and climate-adaptive species selection. Ultimately, understanding tree oscillation informs biomimetic design and supports interdisciplinary strategies for enhancing forest resilience and sustainable environmental planning.

**Keywords:** Aerodynamic interaction, Climate resilience, Damping, Forest stability, Resonance, Structural adaptation, Tree biomechanics, Wind-induced oscillation.

### Introduction

Trees are not static structures; they are living, dynamic systems that continuously interact with their physical environment. Among the most influential environmental forces is wind, which imposes variable mechanical loads that trees must resist, dissipate, or adapt to over their lifetimes. These loads generate oscillatory movements—commonly described as tree swaying or dancing—that arise from the interplay between aerodynamic forces and the mechanical properties of trunks, branches, and foliage<sup>1,2</sup>. Unlike engineered structures, trees are capable of modifying their form and material composition in response to mechanical stress, a process known as thigmomorphogenesis, which allows them to optimize strength,

flexibility, and stability under recurrent wind exposure<sup>3</sup>.

Wind-induced oscillation influences nearly every structural and functional component of a tree. At the whole-tree scale, oscillation determines how force is transmitted from the canopy down through the trunk to the root–soil interface, affecting bending moments, resonance behavior, damping capacity, and risk of mechanical failure<sup>4</sup>. At the tissue level, cyclical bending modulates cambial activity, wood density, and grain orientation, resulting in growth patterns specifically adapted to local wind climates<sup>5</sup>. Even canopy architecture—such as leaf clustering, branch distribution, and crown shape—evolves partly as a response to aerodynamic loading, altering drag properties and flow patterns<sup>6</sup>.

Understanding biomechanical oscillation is essential for multiple fields:

- *Forestry and Forest Management*

Oscillation data inform storm-damage modelling, help identify species or stands at high windthrow risk, and guide silvicultural treatments such as thinning, spacing, and pruning to reduce vulnerability<sup>7</sup>. Long-term forest planning increasingly incorporates wind-risk simulations as climate-change-driven storm intensity grows.

- *Urban Forestry and Risk Assessment*

In urban landscapes, where tree failure poses significant safety hazards, oscillatory behaviour assists in evaluating structural defects, root plate stability, and the influence of built-environment wind tunnels<sup>8</sup>. Integrating biomechanical measurements with tree-risk assessment frameworks enhances public safety and informs maintenance regimes.

- *Ecology and Earth-System Modelling*

Wind–tree interactions shape forest successional dynamics, carbon cycling, and disturbance regimes. Incorporating wind-induced movement into ecological and climate models improves predictions of forest response to extreme weather events and helps refine estimates of global carbon sequestration<sup>9</sup>. Oscillation also affects seed dispersal, microclimate conditions, and canopy turbulence, influencing ecosystem processes at multiple scales.

- *Engineering, Architecture, and Biomimetics*

Tree oscillation provides a rich source of inspiration for structural engineering. The natural ability of trees to balance flexibility and rigidity, avoid catastrophic resonance, and use distributed damping mechanisms has influenced the design of wind-resistant buildings, bridges, and robotic structures<sup>10</sup>. As engineered systems begin to emulate biological

resilience, understanding tree biomechanics becomes increasingly relevant.

- *Climate Change, Storm Regimes, and Future Needs*

Climate change is projected to intensify storm frequency and severity, alter prevailing wind patterns, and increase the incidence of extreme gust events<sup>11</sup>. These changes heighten the urgency of understanding how trees oscillate and fail under complex wind loads. Enhanced biomechanical models can support climate-adaptive forest management, improve urban resilience, and guide conservation strategies aimed at preserving wind-vulnerable ecosystems.

Overall, the study of wind-induced tree oscillation is fundamentally interdisciplinary, bridging biology, physics, ecology, engineering, and climate science. As global wind regimes shift and disturbance events escalate, a deeper understanding of tree biomechanics will be crucial for managing landscapes, ensuring public safety, and designing resilient structures inspired by nature.

## Objectives of the Study

This systematic review aims to:

1. Outline the core mechanical principles and biological functions underlying tree oscillation.
2. Synthesize major historical and current research findings in tree biomechanics.
3. Review common methodologies, tools, and models used to study wind-induced tree movement.
4. Evaluate ecological and structural implications of oscillation for tree stability and adaptation.
5. Identify research gaps and propose priorities for future investigation

## Literature Review

### *Early Mechanical Models (1950–1980)*

Early research in tree biomechanics treated trees as tapered cantilever beams, adopting classical engineering assumptions

to estimate bending stress, elastic modulus, and failure thresholds<sup>12,13,14</sup>. This modelling approach allowed researchers to link trunk geometry to flexural rigidity, laying the foundation for later dynamic wind studies. Pioneering work demonstrated that the second moment of area, wood density, and stem taper strongly influence bending resistance, enabling predictions of stem breakage under strong winds<sup>15,16</sup>.

During this period, research was largely static rather than dynamic. Investigators focused on measuring the modulus of elasticity and its relationship to structural performance<sup>17</sup>. Early experimental work also examined the effects of stem defects and eccentric loading on mechanical stability<sup>18</sup>. Vogel's early contributions further emphasized how material properties and morphology affect drag and mechanical resistance, highlighting the importance of form in wind loading<sup>1,2</sup>.

Although simplified, these early models established essential mathematical and conceptual relationships between load, stiffness, geometry, and material strength<sup>19,20</sup>, forming the basis for later oscillation and vibration research.

#### *Introduction of Oscillation and Resonance Theory (1980–2000)*

By the 1980s and 1990s, a major conceptual shift occurred as trees began to be understood as dynamic vibrating systems rather than static beams. Studies characterized natural frequencies, mode shapes, and damping ratios, demonstrating that trees oscillate in multiple modes influenced by height, taper, and mass distribution<sup>21,22</sup>. Experimental vibration studies showed that increased slenderness reduces natural frequency, increasing susceptibility to resonance under gusty winds<sup>23,24</sup>.

During this phase, attention turned to resonance-driven failures, where repeated gusts synchronizing with a tree's natural frequency amplify sway and

increase structural stress<sup>25</sup>. Aerodynamic excitation, gust penetration depth, and canopy turbulence were identified as key forces driving oscillation<sup>26</sup>. This provided the groundwork for mechanistic wind-damage models such as General Airflow and Loading Effects on Stands (GALES) and the Helsinki WIND model, which incorporate dynamic factors into critical wind speed predictions<sup>27,28,29</sup>.

A parallel line of research explored biological adaptation to mechanical stress. Repeated mechanical stimulation was shown to trigger thigmomorphogenesis, altering growth patterns, stem reinforcement, and cambial activity<sup>30,31</sup>. This created a bridge between structural mechanics and plant physiology, demonstrating that oscillation is both a mechanical response and an adaptive growth signal.

#### *Aerodynamic and Structural Integration (2000–2015)*

From 2000 onward, major advances occurred in linking fluid dynamics with structural biomechanics. A landmark synthesis of fluid–structure interactions emphasized the roles of canopy porosity, turbulence spectra, reconfiguration, and aerodynamic drag reduction<sup>31</sup>. Studies during this period demonstrated that leaves and branches dynamically alter shape to minimize drag, a process known as reconfiguration<sup>32,33</sup>.

At the structural level, significant progress emerged through Finite Element Analysis (FEA). Researchers developed detailed 3D mechanical models of trees incorporating branch topology, wood anisotropy, and dynamic loading<sup>34,35</sup>. FEA enabled simulation of stress transmission from canopy to roots, improving understanding of stem breakage and root plate rotation<sup>36</sup>.

At the same time, Computational Fluid Dynamics (CFD) introduced realistic airflow modelling around individual trees and forest stands<sup>37</sup>. CFD studies analysed wake structures, vortex shedding, and

turbulence generation within canopies<sup>38,39</sup>. These advances allowed researchers to model tree oscillation under unsteady wind regimes rather than simplified static loads.

Forest windthrow models also matured. Improved empirical and mechanistic predictors of storm damage integrated tree height, soil moisture, stand density, and dynamic loading<sup>40,7,41,42</sup>. Together, these aerodynamic and structural developments produced a multidisciplinary integrated framework.

#### *Modern High-Resolution and Multidisciplinary Research (2015–present)*

Recent technological advancements have revolutionized tree biomechanics research. Accelerometers, installed on trunks and branches, enable high-frequency monitoring of oscillation, damping, and resonance events during storms<sup>43,44</sup>. These sensors facilitate continuous measurement of natural frequencies and detect early signs of structural degradation.

Simultaneously, LiDAR technology has transformed canopy motion and structural modelling. Terrestrial Laser Scanners (TLS) generate detailed 3D tree models, allowing creation of Quantitative Structure Models (QSMs) for FEA and CFD simulations<sup>45,34</sup>. Time-series LiDAR and high-speed photogrammetry capture crown deformation under natural wind, providing unprecedented insight into dynamic behaviour<sup>46,47</sup>.

Drone-based imaging offers flexible and scalable monitoring of canopy dynamics across forest stands<sup>48</sup>. Meanwhile, advances in time-resolved CFD, large-eddy simulations (LES), and multi-physics modelling now allow coupling of airflow, branch interaction, and material deformation<sup>26,49</sup>.

Biological research has also progressed, revealing how oscillation influences gene expression, hormonal pathways, and growth plasticity<sup>4,5</sup>. Cross-disciplinary studies integrate meteorology, ecology, and mechanics, improving

understanding of wind–forest feedback loops and storm disturbance regimes<sup>9,42</sup>.

Overall, modern research provides high-resolution, multi-scale insights into tree oscillation, combining structural engineering, plant biology, and atmospheric science.

## **Methodology**

### *Data Sources*

Peer-reviewed publications were systematically collected from major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. These platforms were selected to ensure broad disciplinary coverage across forestry science, biomechanics, structural engineering, and atmospheric sciences. Only full-text accessible and reputable scientific works were considered.

### *Search Terms*

A structured keyword strategy was applied using terms such as “tree biomechanics,” “tree oscillation,” “wind–tree interaction,” “mechanical stability of trees,” “damping in trees,” and “tree resonance.” Boolean operators (AND, OR) were used to refine results, and filters were applied to limit outputs to relevant subject areas such as environmental science, engineering, and biology.

### *Inclusion Criteria*

Studies published between 1980 and 2024 were included if they addressed mechanical or dynamic aspects of trees, including oscillation behaviour, wind loading, structural stability, or material properties. Both empirical field measurements and controlled laboratory experiments were considered, along with computational models such as FEA, CFD, or mechanistic growth simulations. Only peer-reviewed articles with quantifiable or theoretical contributions were selected.

### *Exclusion Criteria*

Studies unrelated to mechanical behaviour—such as purely physiological, genetic, or ecological research without mechanical components—were excluded. Works lacking empirical data, simulation outputs, or methodological transparency were removed. Non-peer-reviewed sources, conference summaries, blogs, and popular articles were also omitted to maintain scientific rigor.

*Data Extraction Process*

For each selected study, key variables were extracted, including oscillation parameters (frequency, amplitude, damping ratio), structural attributes (wood density, Young’s modulus, trunk geometry), and environmental factors (wind speed, turbulence intensity, soil moisture). Additional data on modelling assumptions, measurement instruments, and analytical frameworks were recorded. Extracted information was categorized into thematic

clusters to enable cross-study comparison and synthesis.

**Results**

*Oscillation Characteristics*

Trees exhibit multi-modal oscillation, including trunk sway, branch vibration, and canopy flutter, which vary dynamically with wind turbulence. Natural frequencies typically range from 0.1–2.0 Hz, depending on height, stiffness, and mass distribution. Higher modes are activated under strong gusts, increasing mechanical stress.

Oscillation amplitude increases with wind speed, but trees regulate unstable movement through aerodynamic reconfiguration, internal damping, and structural energy dissipation. These mechanisms reduce the likelihood of resonance—a condition where wind forcing frequency matches natural frequency and amplifies sway. The key oscillation parameters identified across studies are summarized in Table 1.

**Table 1. Summary of Key Oscillation Parameters Identified in the Literature.**

Parameter	Typical Range / Behaviour	Determinants	Notes
Natural frequency	0.1 – 2.0 Hz	Tree height, stiffness, mass distribution	Lower in tall flexible trees
Oscillation amplitude	Increases with turbulence	Drag, crown size, flexibility	Higher in leaf-on conditions
Damping ratio	2–15%	Wood anatomy, soil–root interaction	Higher damping reduces resonance
Mode shapes	Multi-modal	Branch geometry, crown asymmetry	Higher modes in strong wind
Resonance sensitivity	Moderate–high	Frequency matching between wind & modes	Frequent in young slender trees

*Structural Determinants*

Mechanical behaviour during oscillation is shaped by trunk, branch, and wood properties. Trunk tapering lowers basal stress and enhances safety margins, while branching complexity distributes aerodynamic loading and increases damping through torsion and friction.

Wood density, fibre orientation, and microfibril angle influence stiffness and

energy absorption. Root structure—including taproot depth, lateral spread, and fine-root density—controls anchorage strength and determines sway frequency.

*Environmental Determinants*

Environmental factors strongly influence how trees oscillate by altering both external wind forces and internal mechanical responses. Soil moisture and

soil type play a central role in root anchorage: saturated soils reduce shear strength and increase sway and uprooting risk, whereas dry or cohesive soils provide greater anchorage but limit natural damping. Clay soils may weaken after storms due to retained moisture, while sandy soils drain quickly but often provide lower frictional resistance.

Wind exposure and turbulence patterns further shape oscillation behaviour. Open-grown trees face stronger, more uniform wind loads that generate large sway amplitudes, whereas forest-grown trees experience filtered winds that reduce trunk motion but increase high-frequency canopy vibrations. Local topography or nearby structures can introduce turbulent eddies that excite higher vibration modes and raise dynamic stress.

Seasonal and atmospheric conditions also modify oscillation dynamics. Leaf presence greatly increases aerodynamic drag—often doubling it—thereby amplifying sway and canopy flutter. In leaf-off seasons, trees experience reduced drag and tend to oscillate primarily in low-frequency modes. Temperature and humidity affect wood moisture content, which in turn influences stiffness: humid conditions soften wood and lower natural frequencies, while dry air stiffens tissues and may heighten resonance risk. Together, these environmental variables create a complex, dynamic matrix that governs how trees respond mechanically to wind. The major structural and environmental factors influencing tree oscillation are summarized in Table 2.

**Table 2. Structural and Environmental Factors Influencing Tree Oscillation.**

Category	Factor	Influence on Oscillation	Mechanism
<b>Structural</b>	Trunk taper	Reduces bending stress	Efficient material distribution
	Branch architecture	Higher damping, load dispersion	Multiple vibration pathways
	Wood density	Higher stiffness	Affects Young's modulus
	Root system	Controls anchorage & sway	Soil–root friction
<b>Environmental</b>	Soil moisture	Wet → more sway; dry → stiff	Changes shear strength
	Leaf state	Leaf-on ↑ drag; leaf-off ↓ drag	Aerodynamic area
	Wind turbulence	Increases irregular motion	Excites higher modes
	Stand density	Dense stands buffer wind	Reduces wind penetration

*Adaptive Responses*

Trees adapt structurally and physiologically to recurring wind stress through thigmomorphogenesis, developing reaction wood (tension wood in angiosperms, compression wood in conifers) that increases stiffness and resistance to bending. Chronic wind exposure promotes thicker stems, shorter heights, streamlined crowns, and branch

reorientation that reduce drag and mechanical strain. Natural pruning removes weak attachments, while root systems strengthen and expand laterally to enhance anchorage and energy dissipation. At the cellular level, mechanical signals alter growth processes by modifying cellulose deposition, microfibril angles, and cell wall structure. Together, these anatomical, morphological, and biochemical

adjustments improve long-term stability and reduce vulnerability to wind-induced oscillation.

#### *Effects of Climate Stress*

Climate change intensifies wind regimes, storm frequency, and soil instability, increasing mechanical loads that elevate risks of windthrow, stem breakage, and crown failure. Strong, irregular gusts now excite higher oscillation modes that can exceed tree strength limits. Drought further reduces root anchorage, increases wood brittleness, and weakens hydraulic function, creating greater sensitivity to wind despite lower canopy drag. Heat stress accelerates wood fatigue, while pest outbreaks and soil erosion compound structural weakening. Collectively, these interacting climate-driven stressors alter forest composition toward shorter, more flexible species and fundamentally reshape biomechanical resilience at both individual and ecosystem scales.

#### **Analysis**

##### *Mechanical Analysis*

Trees act as damped harmonic oscillators, exhibiting complex multi-modal oscillations under wind loading. Trunk sway, branch vibration, and canopy flutter interact to produce non-linear dynamic responses<sup>44,45</sup>. Wind turbulence remains the primary driving force, with gustiness and turbulence intensity controlling the activation of higher vibration modes<sup>26,34</sup>.

Internal damping mechanisms arise from the viscoelastic properties of wood, energy dissipation at branch junctions, and collision or friction between branches and leaves<sup>2,30</sup>. Structural characteristics such as trunk taper, branching complexity, and root architecture regulate stiffness and natural frequencies<sup>13,19</sup>. Observed oscillation amplitudes reflect a balance between aerodynamic forcing and mechanical damping, allowing trees to maintain stability under repeated wind events<sup>44</sup>. This mechanical behavior highlights how natural

structural optimization enables trees to resist catastrophic failure even under stochastic wind regimes.

##### *Ecological Analysis*

Oscillation has significant ecological and functional consequences beyond mechanical stability. In wind-pollinated species, oscillatory motion enhances pollen dispersal, improving reproductive success<sup>3</sup>. Canopy movements dynamically redistribute leaves, optimizing light interception and photosynthetic efficiency in varying wind conditions<sup>5</sup>.

Dynamic stress redistribution reduces the probability of trunk failure by preventing localized overloading and promoting energy dissipation across multiple structural components<sup>14</sup>. Furthermore, mechanical feedback from oscillation stimulates adaptive growth responses, including reaction wood formation and root system remodelling, allowing trees to adjust their structure to prevailing environmental stresses<sup>3,45</sup>. These ecological benefits demonstrate that oscillation is not merely a passive response to wind but an active driver of structural adaptation and ecosystem function.

##### *Applied Analysis*

Understanding tree oscillation has practical applications in forestry, urban planning, and bio-inspired engineering. In urban forestry, detailed knowledge of damping, natural frequencies, and wind-load response informs tree risk assessments, helping reduce hazards from windthrow or branch failure near buildings and roads<sup>7,8</sup>.

In forestry and ecosystem management, oscillation studies guide species selection for wind-prone areas and inform planting densities that optimize mechanical stability while supporting ecological function<sup>42,9</sup>. Mechanical principles derived from trees are also applied in structural engineering and biomimetic design, inspiring flexible constructions, damping systems, and

energy-dissipating materials capable of withstanding dynamic loading<sup>29,26</sup>.

Additionally, insights into climate stress interactions (e.g., drought, storms) support forest restoration and climate adaptation strategies, promoting resilient stands that maintain ecosystem services under extreme weather events<sup>23,41</sup>.

### Discussion

Wind-induced oscillation is not merely a mechanical reaction but a vital adaptive strategy that enhances tree survival under dynamic environmental forces. Trees balance flexibility and strength, allowing stems and branches to bend and dissipate energy without catastrophic failure. Structural traits such as trunk taper, branching architecture, and root configuration, along with canopy-level aerodynamic interactions, optimize natural frequencies, damping, and sway patterns. Oscillation also stimulates adaptive growth through mechanosensitive pathways, including reaction wood formation and root remodelling, demonstrating a complex, multi-scale biomechanical system<sup>30,5,3,45</sup>.

However, climate change amplifies these mechanical challenges. Increasing storm frequency, erratic gusts, prolonged drought, and heat stress weaken anchorage and wood integrity, while pest outbreaks further reduce structural resilience. These compounded stressors can exceed natural adaptive capacity, necessitating advanced predictive modelling that integrates mechanical, ecological, and climatic variables. Understanding tree oscillation as both a mechanical and ecological strategy is essential for forest management, urban safety, and restoration planning under rapidly changing atmospheric conditions<sup>42,23,4</sup>.

### Limitations

#### 1. *Limited Long-Term and Extreme Event Data:*

Few studies capture tree oscillation under extreme wind events or over extended periods, reducing

understanding of cumulative mechanical stress and fatigue effects.

#### 2. *Inadequate Root–Soil Interaction Knowledge:*

The mechanical behaviour of roots under dynamic loading, especially in varying soil types, remains poorly quantified, limiting predictive accuracy for wind-induced failures.

#### 3. *Simplified Tree Geometry in Models:*

Most biomechanical models oversimplify complex tree structures, ignoring branch architecture, canopy asymmetry, and biological variability across species and age classes.

#### 4. *Environmental and Climatic Gaps:*

Research in tropical, arid, high-altitude, and urban environments is insufficient, and most studies do not fully integrate the effects of climate change, such as altered wind regimes and drought, into mechanical simulations.

#### 5. *Technological and Methodological Constraints:*

High-resolution measurement techniques like accelerometers, LiDAR, and drone-based monitoring are limited in scale and cost, restricting long-term, large-scale studies that capture multi-scale oscillation dynamics.

### Future Scope

Future research in tree biomechanics and oscillation should focus on integrating advanced technologies, modelling approaches, and ecological considerations to enhance understanding and application:

#### 1. *High-Resolution Forest-Scale Motion Mapping:*

Utilizing LiDAR and drone-based surveys to capture detailed canopy and trunk oscillation across entire forest stands.

2. *AI and Machine Learning Models:*

Developing predictive tools that incorporate tree geometry, species-specific mechanical properties, and varying wind regimes to forecast failure risk.

3. *Long-Term Monitoring Systems:*

Implementing continuous, real-time tracking of tree oscillation to assess cumulative stress effects and seasonal dynamics.

4. *Root Biomechanics under Variable Soils:*

Conducting experimental and modelling studies to quantify root anchorage, damping, and soil–root interactions under different soil types and moisture conditions.

5. *Climate-Adaptive Species Selection:*

Using mechanical resilience data to guide forestry and urban planting strategies that optimize survival under evolving wind and climate conditions.

6. *Biomimetic and Structural Engineering Applications:*

Applying insights from tree oscillation and damping mechanisms to the design of flexible, wind-resistant structures and energy-dissipating materials.

## Conclusion

Tree oscillation under wind stress is a complex, multi-scale biomechanical phenomenon that integrates structural, ecological, and environmental dynamics. Trees have evolved flexible stems, specialized branching patterns, and

adaptive root systems that allow them to dissipate energy, reduce mechanical stress, and maintain stability while supporting critical ecological functions such as pollen dispersal, light capture, and growth optimization. Multi-modal oscillation, including trunk sway, branch vibration, and canopy flutter, reflects a finely tuned balance between aerodynamic forcing and internal damping mechanisms, enhanced further by adaptive responses like reaction wood formation and root remodelling.

Despite significant advances through high-resolution measurements, modelling, and computational simulations, key knowledge gaps remain. These include limited long-term data under extreme wind events, incomplete understanding of root–soil mechanics, and insufficient incorporation of climate-induced changes in storm intensity and frequency. Addressing these gaps is essential for improving predictive models and informing practical applications, such as urban tree risk management, climate-adaptive forestry, and biomimetic engineering. Future research integrating advanced monitoring, AI-driven modelling, and biomechanical–ecological frameworks will be critical for enhancing tree resilience, sustainable forest management, and ecosystem conservation under changing environmental conditions.

## Acknowledgments

The authors gratefully acknowledge the support provided by their respective institutions during the course of this study. The authors also thank colleagues and reviewers whose constructive comments helped improve the quality of the manuscript.

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