Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIV, 2025
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

RISK OF WINDTHROWS STANDS WITH VARIOUS STRUCTURES USING VERTICAL DIFFERENTIATION INDEX

Lucian Sorin DOROG

University of Oradea, Faculty of Environmental Protection,
26 General Magheru Street, 410087, Oradea, Romania

Corresponding author email: Lucian Sorin Dorog_dorogsorin@gmail.com

Abstract

This study investigates how different stand structures influence vulnerability to windthrows, using the vertical differentiation index as an analytical tool. Measurements were conducted in three forest districts containing stands with varying structures: even-aged, relatively even-aged, relatively uneven-aged, and uneven-aged. Findings indicate that the vertical differentiation index has subunit values close to zero in even-aged stands and approaches one in uneven-aged stands. A significant inverse correlation was observed between this index and the percentage of wood affected by windthrows. These results underscore the importance of diversifying stand structures in Romanian forest management to mitigate ecological and economic losses.

Key words: *stand structure, windthrows, vertical differentiation index, correlation.*

INTRODUCTION

Due to ongoing climate change, forest stands' increasing vulnerability to extreme weather events, particularly windthrows, is a significant concern. Historically, pure even-aged spruce stands were considered highly susceptible, primarily due to shallow rooting systems (Barbu & Barbu, 1993). However, recent evidence suggests that stand structure and management practices also play a crucial role in determining susceptibility to windthrows (Gardiner & Quine, 2000).

The susceptibility of forest stands can be further increased by soil characteristics and land orography, significantly raising the likelihood and severity of these phenomena, particularly in areas where multiple contributing factors interact simultaneously (Negron-Juarez et al., 2023). Additionally, water retention from precipitation in the tree canopy and soil can amplify the impact of windthrows while also causing rapid fluctuations in stream flow over short periods in mountainous regions (Iovan et al., 2024). The vertical differentiation index serves as a valuable tool for assessing the vulnerability of forest stands to various disturbance factors. By providing insights into stand stability, it aids in the development of resilient forests capable of withstanding extreme climatic events in the future (Valinger & Fridman, 2011).

Windthrows, caused by strong winds, can be categorized based on their intensity and impact into endemic and catastrophic windthrows. Catastrophic windthrows result from extreme weather conditions, involving high-intensity winds that devastate large areas, often affecting thousands of cubic meters of wood. In contrast, endemic windthrows occur more frequently - almost annually - due to moderate-intensity winds and are influenced by a combination of site-specific, meteorological, and stand structure factors. Addressing endemic windthrows is a pressing challenge for forestry management, as their cumulative effects can disrupt forest ecosystems, degrade wood quality, and cause economic and ecological disturbances over time. Without proper intervention, these disturbances may ultimately lead to the fragmentation and deterioration of forest stands. Given the increasing frequency and intensity of windthrows, it is crucial to implement adaptive forestry strategies that enhance stand resilience and promote sustainable forest management (Popa, 2005).

The decline of natural forest structures, coupled with environmental degradation and the growing impact of climate change, has intensified extreme weather events, even in forested areas that were previously considered stable 15-20 years ago - excluding pure spruce stands, which have historically been more vulnerable (Duduman, 2011). Large-scale windthrows were predominantly observed in artificially regenerated spruce stands, highlighting the structural weaknesses of such forests in the face of climatic stressors.

To address these challenges, rational forestry practices grounded in ecological principles must be prioritized.

Sustainable forestry should focus on conservation, protection, and the development of structurally diverse and resilient forest ecosystems that align with contemporary environmental realities (Ichim, 1990).

Over the past few decades, forest management has largely promoted uniform stand structures, minimizing horizontal and vertical differentiation. However, these homogeneous stands have exhibited declining self-protection capacity as they age, making them increasingly vulnerable to external stressors and complicating the implementation of effective management plans. In the forests of Trentino, Italy, researchers have identified key stand structure indices that serve as the foundation for modern management strategies, emphasizing the importance of diversified forest structures (Pastorella & Paletto, 2013).

The size and spatial distribution of trees within a stand significantly influences its overall complexity and ability to fulfill eco-protective functions. Greater structural diversity enhances forest stability and resilience, underscoring the need for management strategies that prioritize stand complexity and adaptability to environmental changes (Peck et al., 2014).

This study aims to analyze the relationship between vertical differentiation index values and windthrow vulnerability to inform sustainable forest management practices. To support this analysis, three locations encompassing various types of stand structures were examined. Data were collected and analyzed, vertical differentiation indices were determined, and the occurrence of disruptive phenomena was assessed probabilistically. The results section presents the findings, which served as the basis for formulating the conclusions.

MATERIALS AND METHODS

Study area

Field data were collected from three forest districts:

- U.P. II Valea Seaca, O.S. Gârda, D.S. Alba - this area consists of pure beech stands and mixed stands of beech, fir, and spruce, with little to no silvicultural interventions. These forests are characterized by complex natural structures that have adapted to the local site conditions. Field observations indicate that windthrows in these stands occur sporadically over small areas. Notably, the gaps created by these windthrows provide ideal conditions for natural regeneration, allowing the forest to recover and evolve without human intervention
- U.P.I Sâniob, O.S. Săcuieni, D.S. Bihor - this area consists of pure and mixed Quercus cerris stands, predominantly even-aged, with a few exceptions. While forestry measures have been consistently applied, the stands exhibit limited structural diversity both horizontally and vertically. According to the analyses conducted in this study, these structurally simplified stands are potentially more vulnerable to disturbance factors.
- U.P. VII Văratec, O.S. Sudrigiu D.S. Bihor - included stands affected by severe windthrows in 2017, characterized by high densities and instability due to insufficient silvicultural interventions (Crainic et al., 2024).

Field observations indicate that stands with simplified horizontal and vertical structures are prone to both isolated and large-scale windthrows, which can occur frequently due to the combined influence of various disturbance factors. To enhance the resilience of these stands against such disturbances, future management strategies should focus on increasing structural diversity.

Data collection and analysis

In the analyzed stands, a minimum of 30 trees were measured, with their closest neighboring trees identified. For each measured tree, the heights of both the tallest and shortest trees within its group were recorded. The vertical differentiation index for each analyzed stand was determined using the equation provided by Ciubotaru & Păun (2014) and Keren et al. (2020):

$$DHn = \frac{1}{N} * \sum \left[\sum \frac{1}{n} \left(1 - \frac{Xijmin}{Xijmax} \right) \right]$$

where:

- DHn is vertical differentiation index;
- N - number of measured trees;
- n - number of neighboring trees;
- Xijmin - minimum tree height in the group;
- Xijmax - maximum tree height in the group.

The relationship between the vertical differentiation index and the percentage of volume affected by disturbance factors was analyzed. Special attention was given to stands with even-aged and relatively even-aged structures, as distinguishing between these two categories in the field can sometimes be challenging. Some stands contain areas that could be classified into either category, despite the management plan specifying only one structure type. For consistency, relatively uneven-aged and uneven-aged stands were analyzed separately using the same approach.

To estimate the risk of windthrows over the duration of the management plan with sufficient accuracy, a probabilistic model was developed, based on the approach proposed by Popa I. (2005). The probabilistic model utilized in this study is expressed as follows:

$$V_{dob} = p_{dec} \cdot pdv_{dec} \cdot V_{ha}$$

where:

- V_{dob} is probable decadal volume of windthrows (m^3/ha/decade);
- p_{dec} - decadal probability of occurrence of windthrows;
- pdv_{dec} - decadal intensity of the windthrows caused by the wind (% of the volume per hectare);
- V_{ha} -volume per hectare.

This model provides an estimation of windthrow risk by quantifying the probable volume of wood affected by wind over a ten-year period.

RESULTS AND DISCUSSIONS

The analysis of the four types of stand structures in relation to their stability against disturbance factors, assessed using the vertical differentiation index, provides valuable insights for both theoretical and practical forest management. Understanding these relationships allows for the development of strategies that minimize stand vulnerability to windthrows. The following section explores how different structural types influence the likelihood of windthrow occurrence.

Windthrows result in significant economic and ecological losses. From an economic perspective, they lead to wood depreciation, increased costs for evaluation and extraction, and difficulties in adhering to forest management plans. Ecologically, they can cause a partial or complete disruption of forest functions, with long-term effects that may take decades to fully manifest. While economic losses can be quantified relatively easily during timber assessment and harvesting, ecological impacts - such as biodiversity reduction, habitat disruption, and changes in microclimatic conditions - are more challenging to measure.

Statistical analyses reveal a strong and consistent correlation between windthrow probability and key stand parameters, including production class, average tree diameter, and height. However, the most influential factor appears to be standing age. Research conducted in the Suceava Forestry District indicates that the highest windthrow susceptibility occurs in stands aged between 60 and 80 years (Popa, 2005).

To estimate the volume of wood likely to be affected, an average value was calculated based on the minimum and maximum values within specific probability intervals. The classification of windthrow intensities is as follows:

- 20-40% probability (Table 1): windthrows at this level are generally low-intensity and occur sporadically across the landscape. These events, often classified as endemic windthrows, are particularly beneficial in uneven-aged and relatively uneven-aged stands, as they promote continuous natural regeneration.
- 40-60% probability (Table 1): windthrow intensity increases slightly, but the events remain localized and do not immediately threaten the overall stability of the stand. These can still be considered endemic windthrows, albeit with slightly higher intensities.
- 60-80% probability (Table 1): windthrows become more concentrated over large areas, indicating structural instability

within the stand. This level of impact highlights the need for urgent management interventions to reduce the volume of affected wood and prevent further stand degradation. Such stands require targeted silvicultural measures to restore their resilience and shift them into structural categories where windthrows remain isolated rather than widespread disturbances.

By integrating these findings into forest management planning, strategies can be refined to enhance stability, reduce economic losses, and ensure long-term ecological sustainability.

The probable volume of wood affected by windthrows follows an increasing trend as the probability class rises. Specifically:

- at the 20-40% probability level, the affected wood volume ranges between 8-10%.
- for the 40-60% probability level, this increases to 13-16%.
- at the 60-80% probability level, the percentage of affected wood reaches 18-22% (Table 1).

Table 1. Probably affected volume per hectare based on probability classes

Average volume per hectare (m^3)	Probability classes (%)		
	20-40%	40-60%	60-80%
	Probable volume affected per hectare (m^3)		
300	24	41	60
400	31	56	79
500	49	80	105
600	60	96	112
700	70	112	154

The similarity between the percentage of wood affected across different probability classes and the harvesting indices at the stand level suggests that regular and well-executed silvicultural interventions reduce the likelihood of windthrows. Field observations reinforce this conclusion, as it stands that systematic and properly executed management practices are significantly less affected by destabilizing factors compared to those with irregular or poorly implemented interventions.

Figure 1 illustrates the relationship between the percentage of wood affected by windthrows and the vertical differentiation index for even-aged and relatively even-aged stands. The data indicate that when the vertical differentiation index is low (0-0.1), windthrow damage is substantial, ranging from 60-80%. However, as vertical differentiation increases, the percentage of affected wood declines sharply. This trend is clearly demonstrated by the regression equation, which has a coefficient of determination (R^2) of 0.63, indicating a strong negative correlation.

For even-aged and relatively even-aged stands, improving vertical differentiation through consistent silvicultural practices can significantly enhance stand stability. The correlation coefficient of -0.55 further supports this relationship, highlighting the crucial role of structural diversity in mitigating windthrow susceptibility (Figure 1).

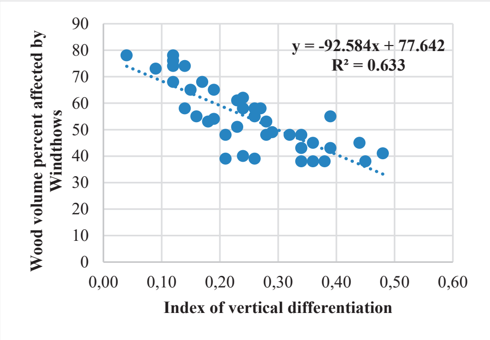

Figure 1. Wood volume percent affected by windthrows in correlation with vertical differentiation index in even-aged and relative even-aged stands

Figure 2 illustrates the relationship between the percentage of wood affected by windthrows and the vertical differentiation index for uneven-aged and relatively uneven-aged stands. The data indicate that these stands experience significantly lower windthrow impact compared to even-aged stands.

A clear downward trend in the regression equation confirms that as the vertical differentiation index increases, windthrow susceptibility decreases. However, in contrast to even-aged stands, the affected wood volume generally remains below 50%, with only a few exceptions.

The coefficient of determination (R^2 = 0.65) closely aligns with the findings for even-aged stands, reinforcing the consistency of this relationship.

For uneven-aged stands, stability can be further enhanced through silvicultural interventions where applicable. However, in cases where

Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XIV, 2025
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

management constraints prevent interventions, maintaining a high vertical differentiation index through continuous natural regeneration proves to be the most effective strategy for reducing windthrow susceptibility.

The correlation coefficient of -0.81 between the percentage of volume affected by windthrows and the vertical differentiation index further supports the strong inverse relationship between these variables, demonstrating that greater structural complexity significantly enhances stand resilience (Figure 2).

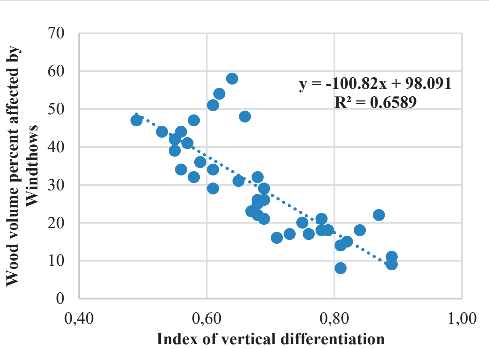

Figure 2. Wood volume percent affected by windthrows in correlation with vertical differentiation index in uneven-aged and relative uneven-aged stands

The percentage of wood likely to be affected by windthrows starts at approximately 10% for windthrow intensities in the 20-40% range. This percentage increases to around 15% for intensities between 40-60% and further rises to an average of 20% for windthrow intensities in the 60-80% range (Figure 3).

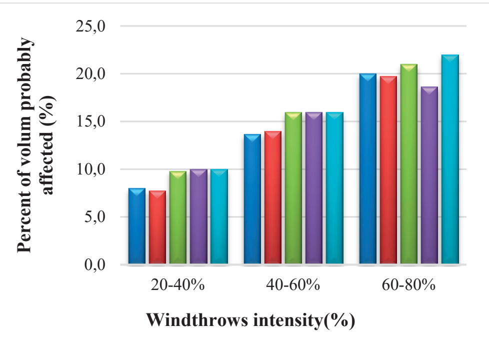

Figure 3. The percentage of volume probably affected in correlation with windthrows intensity

The vertical differentiation index serves as a reliable indicator of stand stability in the face of various disturbance factors. Higher index values, approaching 1, indicate structurally complex and resilient stands where only isolated windthrows occur, often benefiting natural regeneration. Conversely, index values close to zero suggest highly vulnerable stands, where the likelihood of extensive windthrows is significantly increased.

Windthrow probability is also influenced by site conditions, which can either amplify or mitigate the effects of these disturbances. Previous studies have identified three primary factors contributing to windthrows: stand structure, site conditions, and extreme weather events (Popa, 2005).

In the medium to long term, forestry practices must focus on developing uneven-aged stands with high structural diversity, ensuring greater stability against disturbances. The vertical differentiation index not only assesses stand resilience but also provides insights into long-term sustainability. Stands with higher differentiation indices demonstrate strong resistance to disturbances, whereas those with lower values remain highly susceptible (Dorog, 2021).

The impact of climate change is becoming increasingly evident in forests, with more frequent extreme events such as prolonged droughts, heavy rainfall over short periods, and large-scale windthrows affecting entire ecosystems. Findings from this study confirm that stands with both vertical and horizontal structural diversity are significantly less vulnerable to such disturbances. This reinforces the urgent need for Romanian forestry to prioritize diversified stand structures, ensuring they can perform multiple ecological functions effectively.

To address these evolving challenges, forestry regulations and technical norms must be revised to incorporate strategies that reduce damage and enhance stand resilience. The eco-protective role of forests should be evaluated not only in terms of their ecosystem functions but also their structural stability against extreme events.

Future silvicultural interventions must be adapted to align with the new realities brought by intensifying climatic events. In addition to achieving traditional management goals, these interventions should prioritize enhancing stand complexity. Forestry operations should be conducted at low intensities (6-10%), with a maximum threshold of moderate intensities (10-16%), ensuring that no large gaps are created, as these can become weak points for future windthrows.

A localized approach is also essential-forest management strategies should be tailored to specific site conditions, considering regional variations and unique environmental challenges. Implementing adaptive solutions at the local level will be key to increasing stand stability and resilience to combined disturbance factors.

This study serves as a foundation for future research, focusing both on identifying factors that negatively impact forest stability and on developing effective, science-based solutions to mitigate the risks associated with climate-induced disturbances.

CONCLUSIONS

The vertical differentiation index serves as a key indicator of stand structure complexity and stability. In diversified stands (uneven-aged and relatively uneven-aged), the index exhibits subunit values, with figures approaching 1 reflecting a highly organized and resilient forest ecosystem. Conversely, in simplified stands (even-aged and relatively even-aged), the index also takes subunit values, but as it approaches zero, it signifies a simplified and structurally vulnerable forest ecosystem.

A strong negative correlation is observed between the vertical differentiation index and the percentage of wood volume affected by windthrows. In areas where windthrows have severely impacted more than 60% of the stand volume, the vertical differentiation index is typically low (0–0.2). In contrast, in areas experiencing localized or point windthrows, the index tends to be significantly higher (0.7–0.9).

Field observations confirm that stands most affected by disturbance factors are those with simplified structures. These stands, with only minor exceptions, are highly susceptible to windthrows, leading to the loss of significant wood volumes over time. To reduce the long-term risk of stand collapse, forest management should prioritize structural diversification as a preventative measure.

For diversified stands, it is recommended to maintain and further enhance structural complexity to mitigate risks. Notably, these stands experience localized windthrows, which are beneficial as they facilitate continuous natural regeneration and help sustain or even increase structural diversity over time.

In areas with low windthrow probability, the affected volumes remain minimal, aligning with the concept of point windthrows, which naturally support ongoing regeneration and structural maintenance.

In areas with moderate windthrow probability, a higher proportion of stands are affected, leading to progressive structural degradation and increased vulnerability.

In areas with high windthrow probability, the impact is often irreversible, requiring the complete extraction of affected wood, which disrupts the forest’s ecological functions and jeopardizes long-term sustainability.

Both ecological and economic losses are significant in simplified stands, reinforcing the urgent need for structural diversification as a core forest management strategy. The structure of a stand directly influences its stability, and therefore, forest management must prioritize the promotion of diverse, resilient stand structures.

Naturally regenerated stands demonstrate higher stability against disturbances compared to artificially regenerated stands, which often lack the necessary structural complexity.

To enhance the stability of artificially regenerated stands, it is recommended to use genetically selected planting material that aligns with both current and future stand stability requirements.

Moreover, an analysis of harvesting indices in various forestry interventions reveals that stands systematically managed through appropriate silvicultural practices are significantly less vulnerable to disturbances. In contrast, stands with above-normal density and high slenderness coefficients - where interventions are irregular or absent - are at a greater risk of windthrows.

Moving forward, Romanian forestry must adopt complex and adaptive management solutions aimed at diversifying stand structures to minimize ecological and economic damage while ensuring the long-term sustainability of forest ecosystems.

REFERENCES

Barbu, I. & Barbu, V. (1993). Norway spruce (*Picea abies L. Karst*) in Romanian literature (1890-1990). *Bucovina Forestieră, 1*(1-2), 46-52.

Ciubotaru, A. & Păun, M. (2014). *The structure of the stands*. Transilvania University Publishing House Brașov, pp. 169.

Crainic, Gh.C., Irimie, Fl., Cioflan, Fl.M., Dorog, L.S., Iovan, C.I., Șerban, E. (2024). The influence of extrem weather phenomena on the management of hardwood trees. *Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Series E., 13*, 397-407.

Duduman, G. (2011). A forest management planning tool to create highlydiverse uneven-aged stands. *Forestry: An International Journal of Forest Research, 84*(3), 301–314, https://doi.org/10.1093/forestry/cpr014

Gardiner, B.A. & Quine, C.P. (2000). Management of forests to reduce the risk of abiotic damage – a review with particular reference to the effects of strong winds. *Forest Ecology and Management*, *1-3*, 261-277, https://doi.org/10.1016/S0378-1127(00)00285-1

Ichim, R. (1990). *Gospodărirea rațională pe baze ecologice a pădurilor de molid*. Ceres Publishing House, pp. 194.

Iovan, C.I., Sabău, N.C., Dorog, L.S., Covaci, F., Iovan, A.R., Crainic, Gh.C. (2024). Analysis of some parameters of the hydrographic basins in the forest fund. *Scientific Papers*. *Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Series E., 13,* 564-571.

Keren, S., Svoboda, M., Janda, P., Nagel, T.A. (2020). Relationships between Structural Indices and Conventional Stand Attributes in an Old-Growth Forest in Southeast Europe. *Forests, 11*(1), 4. https://doi.org/10.3390/f11010004

Negron-Juarez, R., Magnabosco-Marra., D., Feng, Y., Urquiza-Muñoz, J, D., Riley, W. J., Chambers, J. Q., (2023). Windthrow characteristics and their regional association with rainfall, soil, and surface elevation in the Amazon. Published by IOP Publishing Ltd. *Environmental Research Letters, 18*, https://doi.org/10.1088/1748-9326/acaf10

Pastorella, F. & Paletto, A. (2013). Stand structure indices as tools to support forest management: An application in Trentino forests (Italy). *J. For. Sci., 59*(4), 159-168. doi: 10.17221/75/2012-JFS.

Peck, J.E., Zenner, E.K., Brang, P., Zingg, A. (2014). Tree size distribution and abundance explain structural complexity differentially within stands of even-aged and uneven-aged structure types. *European Journal of Forest Research*, *133*(2), 335-346, https://doi.org/10.1007/s10342-013-0765-3

Popa, I. (2005). Windthrow – Risk factor in mountainous forest. *Analele ICAS, 48*, 3-28.

Valinger, E., Fridman, E. (2011). Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. *Forest Ecology and Management 262*(3), 398-403, https://doi.org/10.1016/j.foreco.2011.04.004