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Phenotypic variability of *Picea abies* characteristics in regard with microstationary ecological conditions

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Abstract

Picea abies (L.) Karst is one of the most significant coniferous tree species in Romania, covering around 24% of the country's total forested area. It plays an important ecological and economic role, being widely used in the timber industry and contributing to biodiversity and climate regulation in mountainous regions. The study conducted in UP II Bistra, managed by the Valea Arieșului Forest District, aimed to assess the ecological response of Norway spruce under varying microstationary conditions across five sample plots, each measuring 500 m². The research focused on the influence of ecological factors such as slope exposition and altitude on growth performance and biomass accumulation. Results revealed that trees located on south-west (S-W) facing slopes, at altitudes between 800–1400 m, showed significantly higher biomass values compared to those on north-east (N-E) exposures, despite similar altitude ranges. Among the factors analyzed, slope exposition was identified as the primary driver of phenotypic variability and forest ecosystem functioning at the landscape level. Given that all studied stands were pure and even-aged, the observed growth differences are likely linked to specific local habitat conditions. The superior growth performance observed on south-western slopes is largely due to the *P. abies* natural preference for semi-shaded environments, where the balance of sunlight and moisture creates optimal conditions for early development and root establishment. Furthermore, the research supports the conservation of biodiversity in the region by highlighting how varying environmental conditions and forest management practices affect species diversity and ecosystem stability.

Keywords: diversity; environment; forest; Norway spruce; variability

Introduction

Forested biomes around the world are vital for terrestrial biodiversity, yet the increasing demand for resources by humans has resulted in the conversion of natural forests to agricultural land and the degradation of forest landscapes through activities such as hunting, logging, fragmentation, pollution, urbanization and other anthropogenic effects [7,24]. In light of these challenges, it is essential to prioritize sustainable management practices that balance human needs with the health of forest ecosystems [25]. Conservation efforts, reforestation initiatives, and stricter regulations on resource extraction can help mitigate the impacts of human activities, ensuring that forested biomes continue to thrive and support global biodiversity for future generations [28,1].

Climate change is currently recognized as one of the most significant threats to global biodiversity, exerting both direct and indirect effects on tree growth and forest productivity. Such an impact can lead to substantial ecological imbalances, undermining the functioning of forests and their ability to provide essential ecosystem services as carbon sequestration and water regulation solutions [12,18].

Picea abies (L.) Karst., commonly known as Norway spruce, is one of the most important coniferous species in Europe, valued for its ecological, economic and soil protection roles, widely distributed across the continent's mountainous regions. In Romania, the species occupies approximately 24% of the national forested area and plays a pivotal role in montane ecosystems, contributing to hydrological regulation, soil stabilization, carbon sequestration, and biodiversity conservation [9,29].

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Evaluating forest diversity, reproductive traits, adaptability and growth on this species is essential for the conservation of genetic resources and the development of effective forest management strategies [26,5]. Amid rising climatic extremes and increasing anthropogenic pressures on forest ecosystems, thus assessing the phenotypic variability of Norway spruce has become critical to understanding species resilience and adaptive potential. Its variability is influenced by a set of microecological factors, such as slope aspect, elevation, soil moisture, and light regime - that can generate significant differences in growth performance and biomass accumulation even within a small forest area [11,17]. That pointed out, the hereby study underscores the role of microstationary environmental factors, especially slope exposition, in driving phenotypic variability and biomass accumulation in *Picea abies* stands.

Long-term provenance trials confirm that *P. abies* exhibits high phenotypic plasticity, responding distinctly to localized climatic and edaphic conditions [9]. Moreover, early-stage physiological and biochemical adaptations play an essential role in long-term regeneration success. Several authors [25,14], demonstrated that both provenance and abiotic stress significantly influence germination capacity and seedling resilience - phenomena similarly documented in other forest species [27], but also exotic ones such as *Calamus rhabdocladus* [15].

Considering the forest landscape scale, the interaction between stand structure, topography, and precipitation patterns affects not only productivity, but also ecological stability. Recent Romanian studies have highlighted the value of forest watershed restoration and ecological reconstruction in mitigating erosion and improving the efficiency of ecosystem-based investments [2]. Additionally, other researches [3,23] have shown that early silvicultural interventions, such as the application of biostimulants and consideration of seed provenance, can significantly influence later phenotypic outcomes.

Beyond these regional findings, the international literature emphasizes that *P. abies* is highly sensitive to climate-induced stress, particularly in ecotonal zones where water and heat stress reduce vitality [8,6]. In this context, adaptive forest management strategies must be informed by a robust understanding of phenotypic variability and local ecological feedbacks [4,21].

The current study, conducted in Production Unit II Bistra (Valea Arieșului Forest District), investigates the ecological response of *P. abies* under variable microstationary conditions. Using different sample plots, distributed across a gradient of elevation and slope exposition, the research aims to identify key environmental drivers influencing growth performance and biomass accumulation in pure, even-aged Norway spruce stands. The findings offer relevant insights for biodiversity conservation and sustainable forest management in montane regions, where ecological heterogeneity fundamentally shapes forest structure and function.

The current findings contribute with valuable insights into species specific ecological responses, supporting the development of site adapted forest management practices, aimed at enhancing ecosystem resilience and promoting sustainable biodiversity conservation.

Material and Method

The overarching objective of this study was to deepen the understanding of the phenotypic expression and ecological behavior of *P. abies* in relation to varying microstationary conditions. By analyzing the species' growth characteristics under site specific environmental gradients, the research aims to support adaptive forest management strategies, while simultaneously contributing to the conservation and sustainable use of *P. abies* dominated habitats (Figure 1). The goal of analyzing the characteristics and peculiarities of Norway spruce was to enhance the understanding and proper management of this species, promoting also the protection of its habitats.

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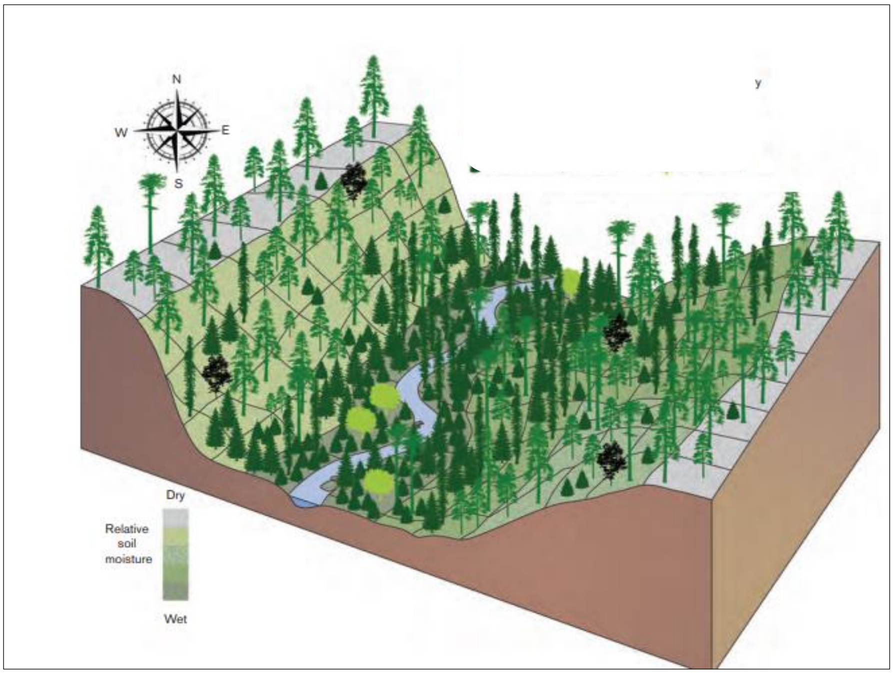

Figure 1. Landscape and forest density vary with topographic features such as slope, aspect, and slope position (Adapted from Malcolm N. *et al*., 2016)

The biological material analyzed consisted of Norway spruce trees originating from Production Unit II Bistra, located within the jurisdiction of the Valea Arieșului Forest District in the Apuseni Mountains. This unit was selected due to its representability of typical montane *P. abies* ecosystems and its ecological heterogeneity in terms of topographic exposure and elevation. The evaluated trees were selected as representative samples for analyzing growth dynamics and ecological responses under varying site conditions.

Five circular sample plots (namely P1-P5), each with a surface area of 500 m², were established as the primary research sites (Figure 2). These plots are situated along an altitudinal gradient ranging from 800 to 1400 meters above sea level and are distributed on contrasting slope aspect - south-west (S-W) and north-east (N-E) - to capture the influence of solar radiation and moisture regime on growth patterns. The differentiation in exposure serves as a natural experiment to assess how environmental variables influence the phenotypic performance of *P. abies* trees across similar climatic zones. All stands studied were pure (monospecific) and of uniform age, facilitating a comparative assessment of the effects of environmental conditions on phenotypic variability of trees, thus ensuring that variations in growth traits could be attributed primarily to site conditions rather than stand composition or age structure.

The analysis included key parameters such as growth performance throught tree volume, quality class, and other relevant ecological factors for each plot, as guided by specialized literature. The study focused on a core set of biometric and ecological variables, including tree height and diameter at breast height (DBH), determined through standardized forest inventory methods, in accordance with current silvicultural and ecological field research protocols.

This approach provided a consistent comparative framework for evaluating the main ecological drivers influencing phenotypic variability in *P. abies*, thereby offering valuable insights into the species' adaptability, performance under site-specific conditions, and implications for long-term forest management planning across heterogeneous landscapes.

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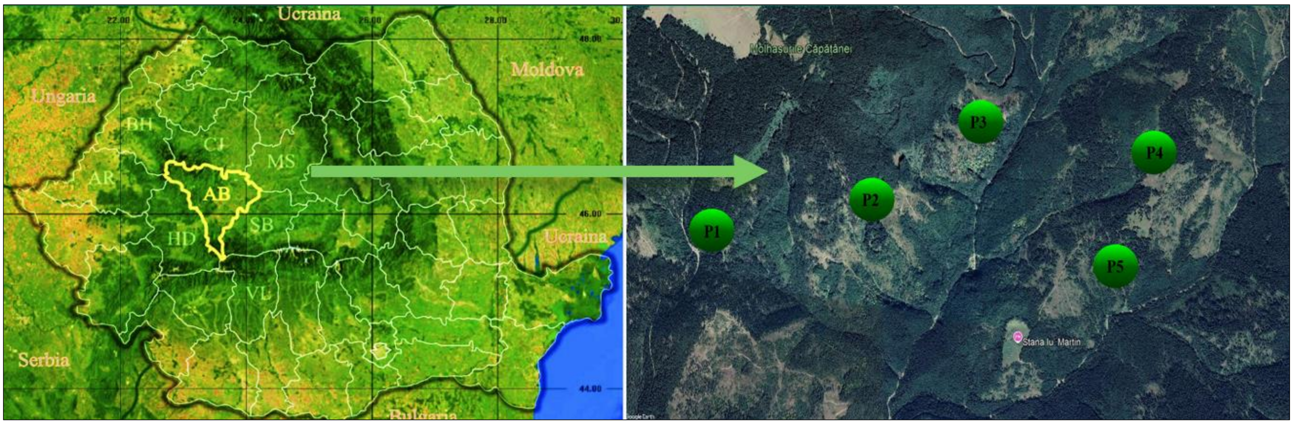

Figure 2. Location of *Picea abies* sample plots studied within the comparative assessment of the effects of environmental conditions on phenotypic variability of trees

Results and Discussion

Slope exposure was identified as the main factor influencing phenotypic variability and forest ecosystem functioning at the landscape scale in the sample plots. The observed growth differences, attributed to localized habitat conditions, are particularly notable on south-western slopes, where the Norway spruce's preference for semi-shaded environment promotes optimal early development and root establishment. The study also highlights the role of varying environmental conditions and forest management practices in supporting biodiversity and maintaining ecosystem stability in the region.

Impact on trees' height and diameter

Regarding the trees' growth, the tallest and thickest individuals were observed (Figure 3a and b) in Plot 5 which is located on south-west (S-W), while the lowest values for the main growth parameters (height and diameter) were recorded in sample Plot 2.

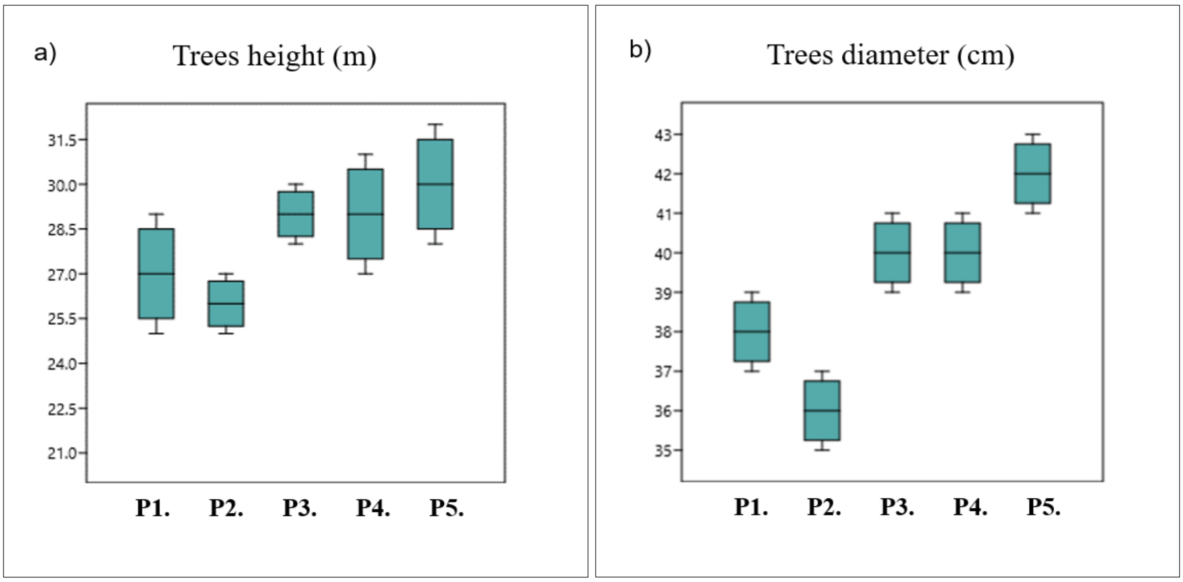

Figure 3. Results regarding tree height (a) and diamter of trees (b) in the analyzed test plots.

The comparative analysis of the morphometric traits of *P. abies* trees across the five sampling plots revealed significant differences influenced by microstationary conditions, particularly in terms of tree height and diameter at breast height (DBH).

With respect to tree height, the most outstanding values were recorded in Plot 5, located on a south-west (S-W) facing slope. Here, the tallest individuals reached heights of up to 30 meters, demonstrating accelerated growth and optimal vegetative development under these conditions. This superior performance can be attributed to a favorable balance between solar radiation, soil moisture, and temperature regime - factors known to support efficient photosynthesis and apical elongation. In contrast, trees in Plot 2, situated on a north-east (N-E) facing slope, exhibited a more modest growth, with the tallest specimens reaching only 26 meters, suggesting environmental constraints that limited vertical development (Figure 3a).

As for the diameter at breast height (DBH), a similar trend was observed. The lowest average diameters were found in Plot 2, reinforcing the pattern of reduced growth performance under less favorable exposure conditions. Conversely, the highest DBH values were observed in Plot 5, aligning with the vertical growth trends and indicating a strong correlation between slope exposition and radial growth (Figure 3b). These findings are consistent with previous studies, which report that sun-exposed slopes tend to promote more effective biomass accumulation due to increased photosynthetic activity [11,9].

Overall, the results support the hypothesis that microstationary variables - particularly slope exposure and elevation - play a decisive role in the phenotypic expression of Norway spruce. They also highlight the importance of tailoring forest management practices to local environmental conditions in order to optimize growth and ecosystem function.

Results regarding the trees' quality class

The assessment of tree quality class across the five test plots revealed a clear dominance of Class I individuals, indicating a high overall performance in terms of structural and growth-related traits. Quality class, a composite index that integrates tree form, vigor, and growth potential, serves as a key indicator of site suitability and silvicultural value.

As shown in Figure 4, most trees across all investigated plots - regardless of slope aspect or elevation belonged to Class I, with particularly high frequencies recorded in P4 (S-W) and P3 (S-W), where 12 and 11 individuals, respectively, were classified in this top category. The obtained results suggest that southwest-facing slopes offer optimal conditions for *P. abies* development, reinforcing findings from growth height and DBH analyses. Even in north-east (N-E) facing plots, such as P1 and P2, Class I still accounted for the majority of individuals, though in slightly lower proportions.

Figure 4. Results regarding quality class of the *Picea abies* trees in the analyzed test plots.

The frequency of individuals in Classes II and III was considerably lower, while Class IV occurrences were marginal, indicating an overall robust quality structure in the sampled stands. These results highlight the limited impact of suboptimal individuals and emphasize the uniformity and health of the studied population.

Such a distribution profile reflects favorable microecological conditions across the production unit, and more specifically, the efficacy of forest management practices that have likely contributed to the development of structurally and physiologically superior individuals.

The strong presence of Class I trees across diverse environmental gradients also confirms the adaptability of *P. abies* and supports its continued use in both ecological restoration and commercial forestry settings.

Results regarding the trees' volume

The analysis of tree volume across the five experimental plots within Production Unit II Bistra revealed substantial variation in aboveground biomass accumulation, with significant differences. The average volume per tree ranged between 1.2 m³ and 1.8 m³ (Figure 5), indicating statistically significant differences among the test sites. These differences reflect the influence of microecological gradients on wood production potential, primarily associated with slope exposure and elevation.

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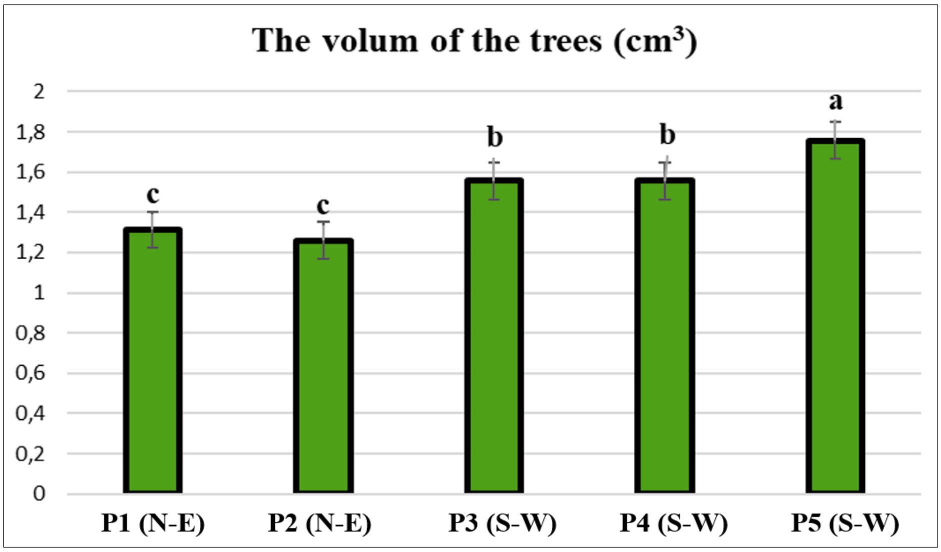

Figure 5. Synthesis of the results regarding the trees' volume in the analyzed test plots. The bars represent the average ± SE. For each plots, different letters from top of the bars indicate significant differences according Tukey's test (α=0.05)

Once again, plot P5 (S-W exposure) recorded the highest mean tree volume (1.8 m³), followed closely by P4 and P3, both also located on south-west-facing slopes. These values reflect optimal growth conditions that likely include greater solar exposure, moderated wind stress, and enhanced soil warmth and moisture availability - factors known to improve radial and vertical growth performance in coniferous species such as *P. abies*. In contrast, lower mean volumes were observed in P1 and P2, situated on north-east-facing slopes, which have reduced insolation and are potentially cooler, thus wetter microclimates may have limited biomass production. Similar results regarding the influence of slope exposition on the growth performance of *P. abies* were also reported [16], highlighting the consistency of these ecological trends in montane conditions.

In the context of climate change and the need to capitalize on less favorable or stress-prone sites for *P. abies* growth, the development of genotypes resistant to biotic and abiotic stress factors remains highly relevant [19]. Genetic resources found in natural stands or even plantations may offer valuable opportunities to identify genotypes that are resistant or at least tolerant to various stressors, including frost, drought, or salinity [20].

Assessing the phenotypic variability of *P. abies* in areas such as UP II Bistra is essential for guiding forest management strategies that aim to reduce the negative impact of climate change. The research emphasizes the need for informed forest management practices to enhance biodiversity conservation and ecosystem stability in mountainous regions. The study highlights that slope exposure plays a significant role in the growth performance and biomass accumulation of Norway spruce, with trees on south-western slopes outperforming those on north-eastern slopes. These findings underscore the importance of micro-stationary conditions, such as slope exposure and altitude, in shaping phenotypic variability and ecosystem functioning. This spatial variability emphasizes the role of topographic context in determining tree volume and thus forest productivity. The significant differences across sites support previous research indicating that slope aspect can strongly influence forest growth dynamics by modulating the microclimatic environment, including temperature amplitude, soil nutrient cycling, and evapotranspiration rates [9,17].

Overall, these findings highlight the necessity of incorporating site-specific ecological variables into forest planning and productivity assessments. The volume differences not only demonstrate once again the ecological adaptability of *P. abies*, but also offer actionable insights for forest managers aiming to optimize biomass yield and long-term sustainability through site-based silvicultural strategies.

Conclusions

The results of this study offer important insights into the phenotypic expression, growth performance, and biomass accumulation of *P. abies* across varying microstationary conditions within Production Unit II Bistra. By examining biometric parameters such as height, diameter at breast height (DBH), quality class, and tree volume across differently exposed and elevated plots, the study highlights the critical influence of environmental heterogeneity on the development of this key forest species. One of the most significant findings is the consistent superiority of individuals located on south-western slopes, which exhibited higher values across all analyzed parameters - height, diameter, volume, and quality class - compared to those on north-eastern slopes. These outcomes underscore the importance of slope exposition and topographic features in modulating site productivity and influencing phenotypic variability, even within relatively uniform, even-aged stands.

Understanding the environmental drivers that affect the growth dynamics of *P. abies* is essential not only for optimizing stand-level productivity, but also for preserving the species' adaptive capacity under shifting climatic conditions. Phenotypic plasticity, as revealed in this study, may serve as a natural buffer against environmental stress, offering resilience in the face of increasing ecological uncertainty.

Moreover, the integration of site-specific ecological insights into forest planning enables the formulation of informed, adaptive management strategies. Such approaches are critical for maintaining ecosystem stability, enhancing biodiversity, and ensuring the sustainable use of forest resources in mountainous regions where topographic and climatic variability are pronounced.

Ultimately, this research contributes to a deeper understanding of how *P. abies* interacts with its environment and offers a scientific foundation for guiding future conservation and silvicultural efforts aimed at maximizing ecological and economic benefits from Norway spruce-dominated forest landscapes.

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