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DOUGLAS FIR PERFORMANCE IN ROMANIA: GROWTH INSIGHTS FROM COMMON GARDEN EXPERIMENTS

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Abstract: *Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) is one of the most important non-native conifers introduced to Europe, valued for its rapid growth, versatile timber, and resilience under climate change. In Romania, the Douglas fir was introduced at the end of the 19th century and later tested in international provenance trials. A total of 61 Douglas fir provenances were evaluated across the three Douglas fir trials established in 1977, representing the complete set of genetic material introduced to Romania. Of these, 38 provenances were common to all three trial sites (Aleșd, Făget, and Padeș). We assessed growth performance using tree volume, slenderness index, and basal area as indicators of productivity and stability. Linear mixed models showed that provenance significantly influenced all traits at the Aleșd and Făget trials, whereas at the Padeș trial, provenance effects were significant only for tree volume. The provenance x location interaction was significant, indicating that provenance varied among sites. Strong provenance × location interactions indicated an instability in growth performance across sites. Among North American sources, interior provenances such as Idaho performed consistently well across sites, while coastal provenances from Washington and British Columbia achieved superior productivity at specific locations. Romanian provenances, including Toplița, Piatra Albă, and Anina Buhui, also ranked among the best performers, underlining their adaptive potential. Correlation analyses showed positive relationships between tree volume and basal area, while both growth traits were negatively associated with the slenderness index. Geographic origin variables explained part of the variation: longitude correlated positively with productivity, whereas higher elevation of origin was linked to slower growth and greater slenderness. Our results emphasise the importance of matching seed sources to planting conditions and highlight the potential of Douglas fir for Romanian forestry.*

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1. Introduction

Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) is an important North American conifer with considerable ecological amplitude and high economic importance. Well-known for its rapid growth and versatile timber, the species has become one of the most significant non-native forest trees in Europe since its early introduction, with its use further supported by international provenance trials established in the 1960s [3, 19, 24]. Provenance trials are essential in forestry for evaluating the adaptive potential of tree species across environments [1]. In the case of Douglas fir, large-scale international provenance trials established under the guidance of IUFRO in the 1960s provided the first systematic basis for identifying well-adapted seed sources for Europe [11, 39]. The drought tolerance of Douglas fir is variable, being influenced by both the genetic origin of provenances and specific soil properties and climate conditions [10, 32].

In Europe, Douglas fir has gained increasing prominence as a productive alternative to Norway spruce, especially under projected climate change scenarios. The species indicates superior drought tolerance compared to several native conifers and broadleaves, positioning it as a candidate for future mixed and protection forests [27, 36].

It comprises two main varieties – coastal (var. *menziesii*), which extends along the Pacific slope from British Columbia to central California, and interior (var. *glauca*), which occupies the Rocky Mountains and interior plateaus from British Columbia southwards into Mexico [35]. These varieties differ in their growth performance and adaptive capacity across environments [16, 23]. Outside its native distribution, Douglas fir has been widely introduced and is now among the most important non-native forest tree species in Europe. Since its first plantings in the early 19th century, it has become naturalised in many regions, with large forested areas established particularly in France, Germany, and Central Europe [19]. In Romania, it was introduced in the late 19th-early 20th century. Since then, Douglas fir has gradually expanded in Romanian forestry, although its distribution has remained limited. At present, the species occupies approximately 7,300 hectares, accounting for about 0.12% of the national forest area [12, 38]. Its rapid growth and adaptability soon encouraged wider use, and since the 1960s it has been tested in international provenance trials, which has confirmed its high potential for Romanian forestry [29].

Although Douglas-fir provenance trials have informed seed-source recommendations across Western Europe (e.g., IUFRO trials), long-term, multi-trait provenance studies in Eastern and Central Europe – particularly Romania – are limited. Remote sensing studies in British Columbia revealed that genetically superior Douglas fir showed taller growth, denser crowns, and greater structural plasticity compared to unimproved stock, demonstrating how genetic gain influences both productivity and stability traits [9]. At broad spatial scales, Douglas fir abundance and productivity in both coastal and interior regions are closely linked to growing-season moisture availability, particularly precipitation and site water balance [5, 15]. Long-term IUFRO provenance trials in Slovenia demonstrated significant differences among Douglas fir seed sources in survival, growth, and log quality, with coastal provenances from Washington showing superior growth and survival [37]. In Romania, Douglas fir has exceeded Norway spruce in growth traits and showed higher resistance and has resilience to extreme droughts, highlighting its potential as a climate-resilient alternative [25].

The main objectives of this study were to: *i)* evaluate the growth performance of tested Douglas fir provenances; *ii)* quantify the effects of provenance on tree volume, slenderness index, and basal are in each trial site; *iii)* analyse the provenance x location (P x L) interaction across sites; *iv)* identify the best-performing provenances for each trait, and *v)* analyse the relationships between traits and the geographic location of provenances.

2. Materials and Methods

2.1. Douglas Fir Provenance Trials in Romania

Douglas fir was introduced to Romania within the framework of the IUFRO programme through a series of common garden experiments established between 1977 and 1980. Of the initial five experimental sites, only three have remained – Aleșd, Făget, and Padeș – all installed in 1977 [11]. These long-term trials included provenances from a wide geographic range of seed sources covering both native and European origins, including 34 provenances from the United States, 10 from Canada (Figure 1c), six from Germany, three from France (Figure 1a) and eight from Romania (Figure 1b). The total of 61 provenances represents the entire set of genetic material tested in Romania. Their distribution across sites was not uniform. Specifically, 55 provenances were tested at Aleșd, 49 at Făget, and 48 at Padeș. A core subset of 38 provenances was common to all sites, enabling comparative analyses of genotype × environment interactions (P X L).

2.2. Experimental Design and Statistical Analysis

The three common garden experiments followed a partially balanced block design. Each provenance was planted in plots of 25 trees, arranged in a 5 x 5 grid with 2 x 2 spacing, with three block replications.

The traits evaluated in the trials were tree volume, slenderness index, and basal area. Tree volume describes the overall productivity of individual trees and was estimated from the diameter at breast height and total height relationship using the regression equation, providing a measure of wood accumulation and growth efficiency. The slenderness index reflects tree stability by expressing the relationship between height and diameter. Higher slenderness values, characteristics of more slender trees, are typically associated with greater susceptibility to abiotic factors [42]. In general, a low slenderness coefficient reflects the presence of a longer crown, a lower centre of gravity, and a well-developed root system. Basal area serves as a reliable indicator of provenance productivity, as it incorporates both tree size and stand density. Basal area is more strongly correlated with tree volume and wood production potential, making it a robust descriptor of provenance-level productivity [31].

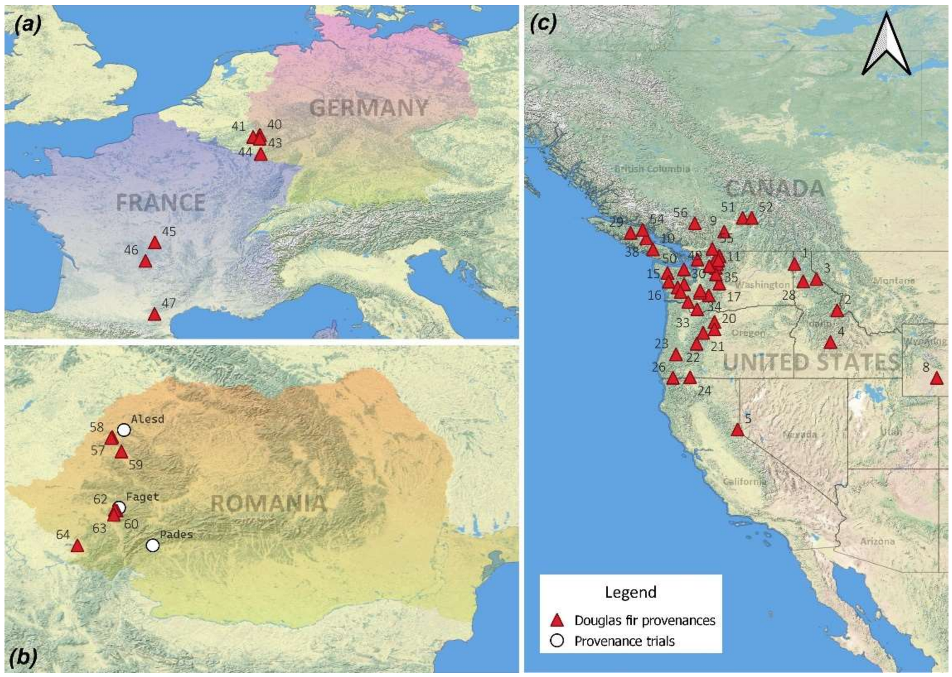

Fig. 1. *Geographic location of the tested Douglas fir provenances (red triangles) and common garden experiments (white circles): a. provenances from Europe, including France and Germany; b. Romanian trial site (Aleșd, Făget, and Padeș) and provenances; c. Native North American provenances from the United States and Canada*

The following formulas were used to calculate the traits:

1. *Tree volume* was determined using the regression equation for forest species in Romania [14] – Eq. (1):

$$\log v = a_0 + a_1 \cdot \log d + a_2 \cdot log^2 d + a_3 \cdot \log h + a_4 \cdot log_2 h \quad (1)$$

where:
v is the tree volume [m^3];
d – the diameter at breast height [cm];
h – the entire height of the tree [m].

The regression coefficients in Equation (1) are for Douglas fir: a_0 = -4.29910; a_1 = 1.90710, a_2 = 0.02841, a_3 = 1.01819, a_4 = 0.055894.

2. *Basal area* (m^2) per tree was calculated using the Equation (2) [2]:

$$BA = \frac{\pi}{4} \cdot DBH^2 \quad (2)$$

where:
BA is the basal area [m^2];
DBH – the diameter at breast height [cm].

The tree-level values were summed to obtain plot-level basal area, and the plot values were then expressed per hectare [m^2/ha].

3. *Slenderness index* per tree was calculated using the Equation (3) [42]:

$$SI = \frac{TH}{DBH} \cdot 100 \quad (3)$$

where:
SI is the slenderness index [%];
TH – the tree height [m];
DBH – the diameter at breast height [cm].

2.3 Statistical Analyses

Quantitative genetic variation was analysed at two levels: *i)* within each trial site, and *ii)* across the three sites.

At the level of each trial, we applied a linear mixed model (Equation (4)) in which provenance was treated as a random factor and block as a fixed factor [26]:

$$Y_{ikl} = \mu + P_j + B_k + ejkl \quad (4)$$

where:
Y_{jkl} is the plot mean for tree volume, basal area, and slenderness index;
μ – the overall mean
P_j – the random effect of provenance;
Bk – fixed block effect;
ejkl – the residual error.

From these models, we obtained the variance components for provenance (*Vp*) and residual (*Vr*), and we tested the significance of the random provenance effects using a likelihood ratio test (*LRT*) comparing models with and without the provenance. The results are summarised in Table 1.

For the analysis across sites, we used the subset of 38 provenances common to all three locations and fitted the following linear mixed-effects model (Equation (5)):

$$Y_{ijkl} = \mu + S_i + P_j + B_k + S_i \cdot P_j + e_{ijkl} \quad (5)$$

where:
S_i is the fixed effect of the site (location) effect;
S_i x P_j – the interaction between site and provenance.

The linear mixed-effects models were computed and tested using the *lmerTest* [21] package in R [30]. Model parameters were estimated using the REML method. For the across-site model (Equation (5)), we obtained an analysis of variance (ANOVA) table for the fixed effects (provenance, location, and P X L). Model fit was verified by checking Q-Q plots and residual versus fitted plots to ensure normality and homoscedasticity of residuals. Pearson's coefficient was used to assess the correlations between traits and geographic variables at each trial. The analysis assumes normally distributed variables and evaluates correlations ranging from -1 (negative) to +1 (positive), with 0 indicating no linear association. Correlation matrices were illustrated with ellipse-based correlograms generated using the *corrplot* [43] package in R. Geographic variables: latitude (°N), longitude (°E), and altitude (m a.s.l) were obtained for each provenance based on the coordinates of their original collection sites and used to analyse correlations between geographic origin and growth traits.

3. Results

3.1. Genetic Variation and Variance Components

The analysis of variance components from the single-site mixed-effects models indicated significant provenance effects for all traits, but the proportion of explained variance varied across trials (Table 1).

At Aleșd, provenance significantly influenced all traits (tree volume, slenderness index, and basal area), with provenance effects accounting for 9.5% of the total variance in tree volume, 4.3% in slenderness index, and 10.3% in basal area. At Făget, provenance effects were also significant for all traits, though the explained variance was smaller: 2.9% for tree volume, 3.2% for slenderness index, and 5.3% for basal area. In contrast, at Padeș, provenance effects were weaker: tree volume showed a significant but low proportion of explained variance (2.9%), whereas slenderness index (0.3%) and basal area (3.9%) were not significantly affected by provenance. Block effects (MSb) were significant only for certain traits, most notably basal area at Făget (p ≤ 0.01), while residual variance consistently accounted for the majority of the variation across all trials (ranging from 89.7% to 99.7%).

Variance components and significance of provenance effects for Douglas fir traits in each common garden experiment Table 1

Trial	Trait	LRTp	Vp	Vr	MSb
Aleșd	Tree volume	18.53 ***	0.06 (9.5%)	0.57 (90.5%)	0.25 ns
	Slenderness index	12.09 ***	0.001 (4.3%)	0.022 (95.7%)	0.17 **
	Basal area	19.27 ***	2.42 (10.28%)	21.11 (89,72%)	20.11 ns
Făget	Tree volume	9.07 **	0.01 (2.9%)	0.34 (97.1%)	5.65 ***
	Slenderness index	6.86 **	0.001 (3.2%)	0.03 (96.8%)	0.57 ns
	Basal area	8.92 **	0.68 (5.33%)	12.07 (94.67%)	131.31 **
Padeș	Tree volume	9.07 **	0.01 (2.9%)	0.34 (97.1 %)	5.65 ***
	Slenderness index	2.07 ns	0.0006 (0.3%)	0.22 (99.7%)	0.22 ns
	Basal area	3.30 ns	0.63 (3,86%)	15.69 (96.14%)	0.31

Note: Significance levels: $p \leq 0.05$ (*), $p \leq 0.01$ (**), and $p \leq 0.001$ (***); ns: not statistically significant with $p > 0.05$; *LRTp* – likelihood ratio test for provenance effect; *Vp* – variance for provenance random effect; *Vr* – residual variance; MS – mean squares for block (b); the values in brackets report the proportion of variance accounted for by each effect.

3.2. Provenance Performance Across Common Garden Experiments

In the Aleșd trial, the provenances with the highest tree volume were 2 – Idaho (U.S.A.), 63 – Nădrăgel, 62 – Vîrful Dăii (Romania), 59 – Toplița (Romania), and 11 – Duncan (Canada) – Figure 2c. For basal area, the highest values were obtained by 40 - Daun Ost, Abt. 46 C. (Germany), 36 - Skycomish, Beckler Peak (Washington, U.S.A.), 58 – Piatra Albă (Romania), 14 – Snohomish, Sloan Creek (Washington, USA), and 1 – Idaho (U.S.A.) – Figure 2a. Regarding the slenderness index, the most stable were 2 – Idaho (U.S.A.), 9 – Merrit (British Columbia, Canada), 64 – Anina Buhui (Romania), 59 – Toplița (Romania), and 47 – Moussans II (France) – Figure 2b.

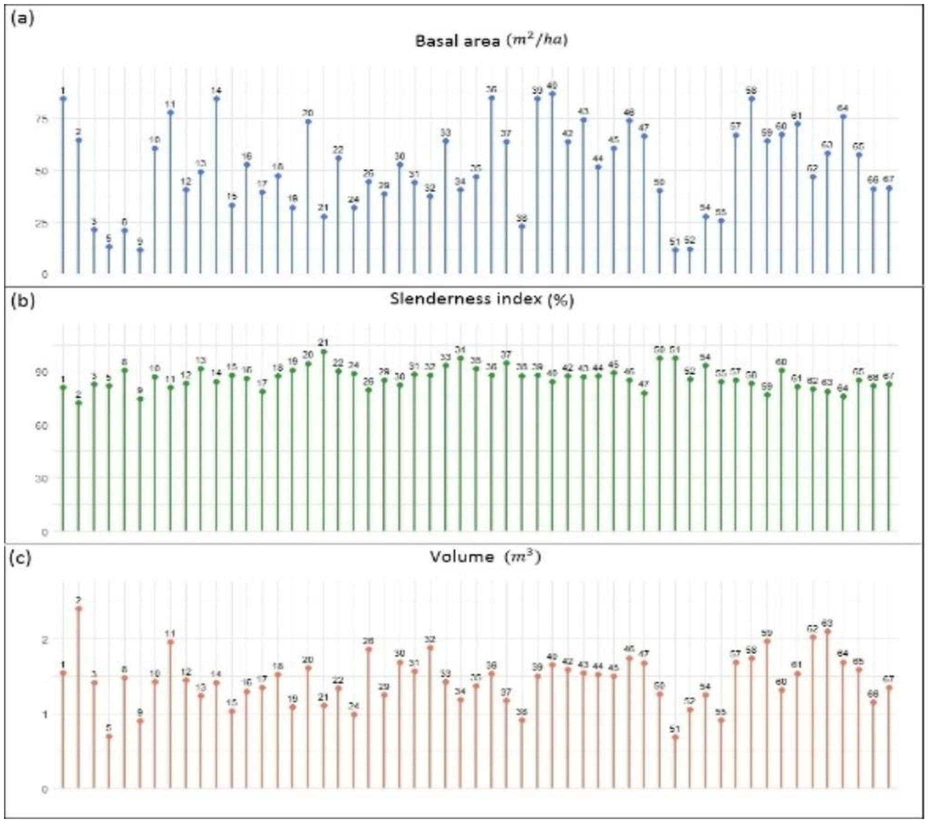

Fig. 2. *Variation in basal area (a.), slenderness index (b.), and tree volume (c.) of Douglas fir provenances at the Aleșd trial*

In the Făget trial, the provenances with the highest tree volume were 55 – Centre Creek, Chilliwack Valey (British Columbia, Canada), 2 – Idaho (U.S.A.), 66 – Elbe (Washington, U.S.A.), 41 – Prüm Süd, Abt. 79 C. (Germany), and 50 – Clallam Country, Louella (Washington, U.S.A.) – Figure 3c. For basal area, the highest values were obtained by 64 – Anina Buhui (Romania), 58 – Piatra Albă (Romania), 2 – Idaho (U.S.A.), 29 – Vancouver (British Columbia, Canada), and 37 – Concrete, Presentin Creek (Washington, U.S.A.) – Figure 3a. Regarding the slenderness index, the most stable were 55 – Centre Creek, Chilliwack Valey (British Columbia, Canada), 4 – Boise (Idaho, U.S.A.), 17 – Kittias, Cle Elum (Washington, U.S.A.), and 56 – Devine Dist. (British Columbia, Canada) – Figure 3b.

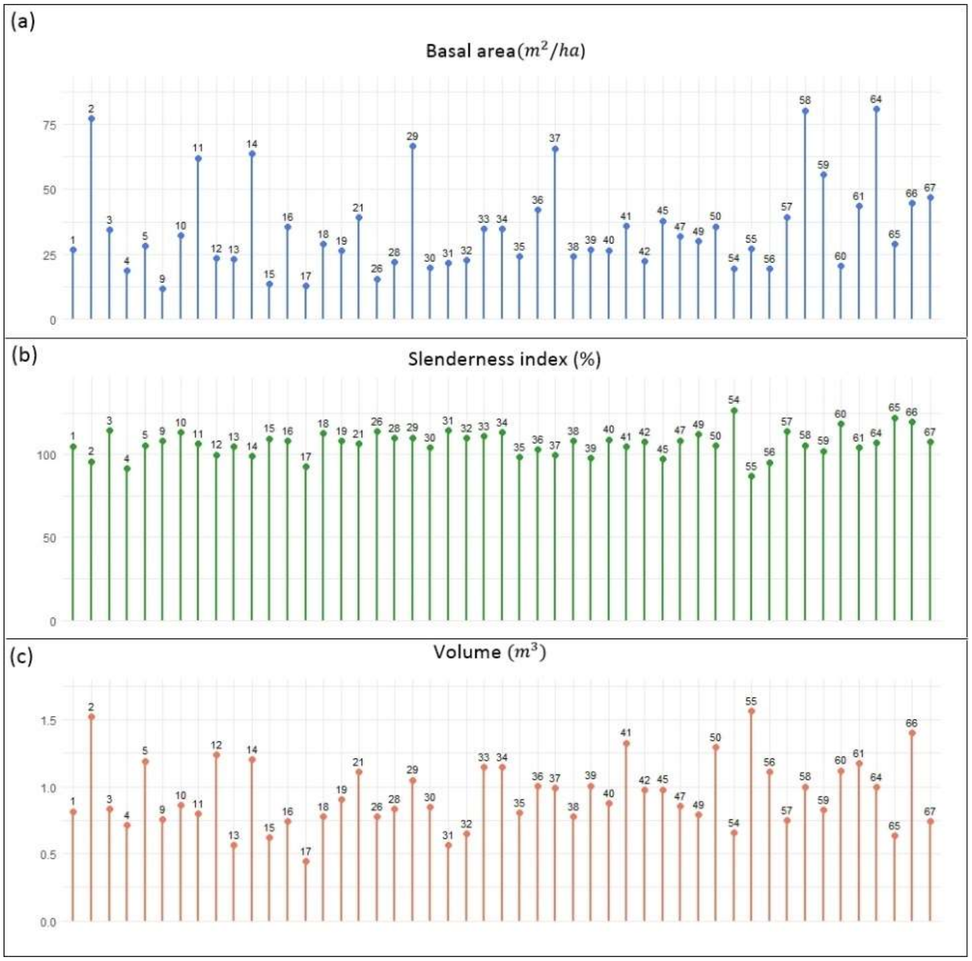

Fig. 3. *Variation in basal area (a.), slenderness index (b.), and tree volume (c.) of Douglas fir provenances at the Făget trial*

In the Padeș trial, the provenances with the highest tree volume were 31 – Elma (Washington, U.S.A.), 37 – Concrete, Presentin Creek (Washington, U.S.A.), 54 – Morton Lake (British Columbia, Canada), 46 – Les Farges III (France), and 34 – Vicinity, Mineral Walker Road (Washington, U.S.A.) – Figure 4c. For basal area, the highest values were obtained by 45 – Poinsat, Puy de Dome (France), 59 – Toplița (Romania), 3 – Idaho (U.S.A.), 11 – Duncan (British Columbia, Canada), and 10 – Franklin River (British Columbia, Canada) – Figure 4a. Regarding the slenderness index, the most stable were 28 – Chatcolet, S. (Idaho, U.S.A.), 2 – Idaho (U.S.A.), 31 – Hoodsport (Washington, U.S.A.), 19 – Pine Grove (Oregon, U.S.A.), and 34 – Vicinity, Mineral Walker Road (Washington, U.S.A.) – Figure 4b.

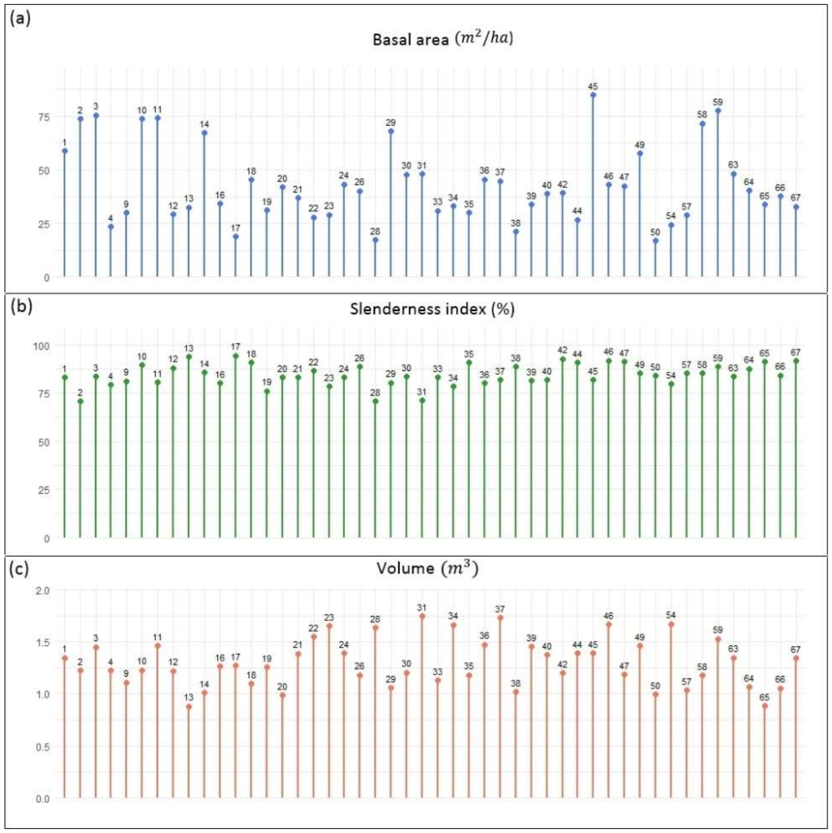

Fig. 4. *Variation in basal area (a.), slenderness index (b.), and tree volume (c.) of Douglas fir provenances at the Padeș trial*

3.3. Provenance x Environment Interaction

The ANOVA of the across-site mixed-effects model (Equation (5)), based on the subset of 38 provenances common to all three sites, was used to assess the effects of provenance (*P*), location (*L*), and their interaction (*P x L*) on trait variation.

Results for traits in Douglas fir across common garden experiments Table 2

Source of variance	Mean square			
	D.F.	**Tree volume**	**Slenderness index**	**Basal area**
Provenance (*P*)	37	0.235 **	0.009 ns	2379.8 ***
Location (*L*)	2	6.768 ***	1.388 ***	8953.6 ***
Interaction (*P x L*)	74	0.239 ***	0.11 *	868.1 ***
Error	189	0.11	0.008	416.5

Note: Significance levels: $p \leq 0.05$ (*), $p \leq 0.01$ (**), and $p \leq 0.001$ (***); ns: not statistically significant with $p > 0.05$.

The analysis of variance showed that tree volume was significantly influenced by provenance ($p \leq 0.01$), location ($p \leq 0.001$), and their interaction ($p \leq 0.001$) (Table 2). For the slenderness index, location had a highly significant effect ($p \leq 0.001$), while the provenance × location interaction was also significant ($p \leq 0.05$); however, the main effect of provenance was not significant. In the case of basal area, all sources of variation were highly significant ($p \leq 0.001$ for location, provenance, and P × L), with location explaining the largest proportion of variance (Table 2).

3.4. Correlations Between Traits and Geographic Variables

The correlation analysis (Figure 5) showed that tree volume was positively correlated with basal area (r = 0.62) and longitude (r = 0.46), while showing a negative correlation with slenderness index (r = -0.47). Basal area was positively correlated with longitude (r = 0.52), but negatively correlated with altitude (r = -0.23). Slenderness index showed weak positive correlation with latitude (r = 0.12) and negative correlations with longitude (r = -0.29) and altitude (r = -0.27).

The correlation analysis (Figure 6) showed a positive relationship between tree volume and basal area (r = 0.36), as well as with longitude (r = 0.14) and altitude (r = 0.19). Tree volume was negatively correlated with slenderness index (r = -0.29). Basal area was positively correlated with longitude (r = 0.28), but negatively with slenderness index (r = -0.11). Slenderness index showed a negative correlation with altitude (r = -0.19), while latitude was strongly negatively correlated with altitude (r = -0.57).

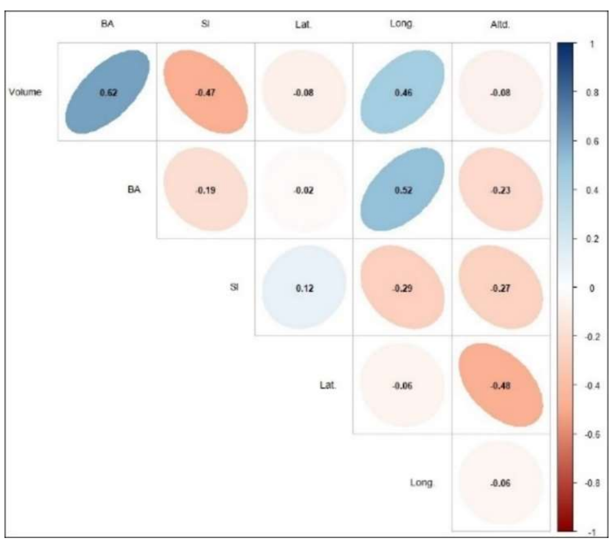

Fig. 5. *Pearson correlation coefficients among tree volume, basal area, slenderness index, and geographic variables (latitude, longitude, altitude) for the Aleșd trial. Positive correlations are shown in blue and negative correlations in red, with the strength of the relationship indicated by colour intensity and ellipse shape*

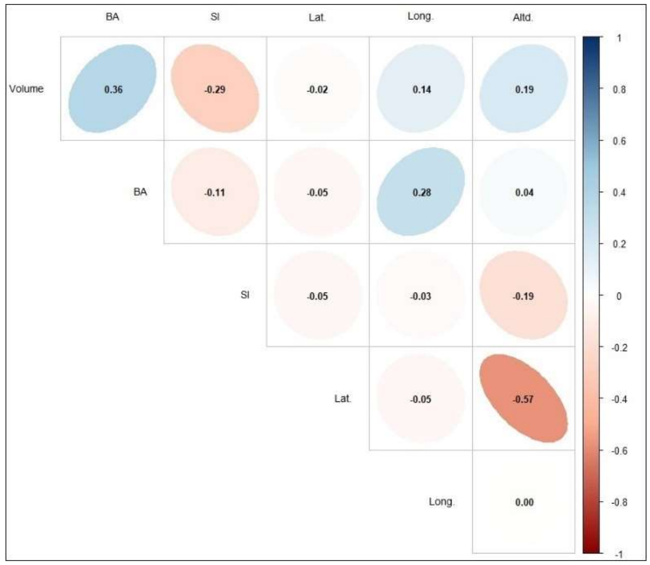

Fig. 6. *Pearson correlation coefficients among tree volume, basal area, slenderness index, and geographic variables (latitude, longitude, altitude) for the Făget trial. Positive correlations are shown in blue and negative correlations in red, with the strength of the relationship indicated by colour intensity and ellipse shape.*

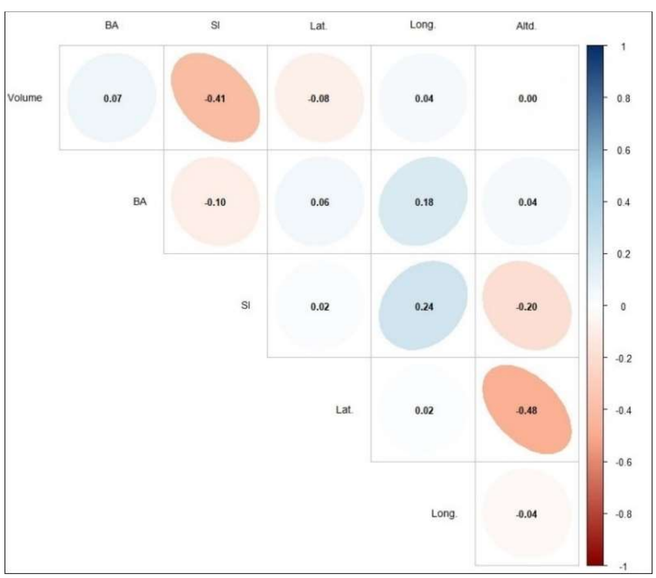

Fig. 7. *Pearson correlation coefficients among tree volume, basal area, slenderness index, and geographic variables (latitude, longitude, altitude) for the Padeș trial. Positive correlations are shown in blue and negative correlations in red, with the strength of the relationship indicated by colour intensity and ellipse shape.*

The correlation analysis (Figure 7) showed that tree volume was negatively correlated with slenderness index (r = -0.41), while its relationships were with basal area (r = 0.07), latitude (r = -0.08), and longitude (r = 0.04). Basal area was positively correlated with longitude (r = 0.18) and negatively with slenderness index (r = -0.10). Slenderness index showed a positive correlation with longitude (r = 0.24) and a negative correlation with altitude (r = -0.20).

4. Discussion

4.1. Genetic Variation and Variance Components

Our results indicated that provenance significantly contributed to variation in tree volume and basal area at Aleșd and Făget, while its influence was weaker at Padeș, where location and the residual component accounted for most of the variation. These results are consistent with findings from other European provenance trials where provenance explained the growth variation, even though site effects and residual variance were larger. In a previous study, provenance explained up to 47% of the variation in the basal area and wood density traits, underlining the importance of genetic differences among provenances [34]. In Douglas fir provenance tests in British Columbia and Oregon, site explained 31-60% of growth variance, while provenance contributed 1-6%; residual variance was also high [20]. The contribution of provenance to tree volume variation in our study (2.9-9.5%) is in line with the Spanish common garden experiments, where provenance significantly influenced height growth in 91 seed sources, with seed source × site interactions explaining 20-50% of variation [41]. This supports our observation that tree volume variation is driven both by genetic differences among provenances and by their interaction with the site. Similar variance patterns were reported in Oregon Douglas fir trials, where family and provenance explained minor variations and site explained most of the variation (approximately 71%), highlighting the major role of environment [4]. In our study, provenance explained between 0.3-10% of the total variance, depending on the trait and site, with the highest contribution observed at the Aleșd trial.

Overall, our results and previous studies [40] confirm that provenance has a significant effect on Douglas fir performance: strong for basal area, moderate for tree volume, and weak for slenderness index.

4.2. Provenance Performance Across Common Garden Experiments

The differences in provenance performance across the three Romanian common garden trials demonstrate the strong influence of P x L interactions in Douglas fir. Provenances that performed well at one site did not always maintain the same ranking, confirming that environmental conditions play an important role in growth. Similar patterns have been reported in other European and North American provenance trials, where growth performance reflected both the climatic similarity between the site of origin and the planting site and the genetic background of the provenances [6, 22].

The performance of provenance 2 – Idaho (U.S.A.) from the interior was the most stable ranking among the highest tree volume and slenderness index at the Aleșd trial, for all traits at Făget, and just for the slenderness index at Padeș. The performance of Idaho provenance in our trials matches results showing that interior provenances grow well when their climate matches the planting site [22].

Among the Romanian provenances, the best performers were 59 – Toplița for tree volume and slenderness index at Aleșd, and for basal area at the Padeș trial, 58 – Piatra Albă for basal area at Aleșd and Padeș, 64 – Anina Buhui for slenderness index at Aleșd and basal area at Făget. All these provenances were ranked in the top five for the analysed traits.

Genetic studies indicate that many productive Douglas fir stands in Europe originated from central Washington seed zones, which aligns with our results that Washington sources performed strongly in Aleșd and Făget [17].

4.3. Provenance x Environment Interactions

Our results showed that variance was divided differently among traits. For tree volume, both provenance and site effects were significant, and their interaction was also important, indicating that while genetic origin matters, the relative ranking of provenances depends on site conditions.

For tree volume, the significant effect of both provenance and location suggests that growth is influenced by genetic differentiation among provenances as well as by environmental conditions [45]. This indicates that the expression of growth potential in Douglas fir is dependent on site and climate, where favourable conditions may enhance genetic performance, whereas less suitable conditions can limit growth regardless of provenance [45].

For the slenderness index, provenance did not show a significant effect, whereas both location and the P × L interaction were significant. This implies that it is more strongly influenced by the site conditions than by genetic origin. The significant interaction effect suggests that provenances respond differently to these site-specific growth conditions, even if no consistent genetic differentiation in slenderness was detected [7, 42].

In the case of basal area, all sources of variation were highly significant, with location explaining the largest proportion of variance. This highlights the dominant role of environmental conditions in determining stand productivity [13].

The significant (P × L) interactions show the genetic performance of Douglas-fir. For example, a long-term provenance trial in eastern Poland, under the influence of a continental climate, demonstrated that growth and survival varied substantially among provenances, highlighting strong P × E effects across contrasting environments [28]. A study assessing the adaptive capacity of Romanian Douglas fir genetic resources found notable variation in growth and climate sensitivity, reinforcing the significance of both genetic background and environmental context for trait expression [25]. In our analyses, location was treated as a categorical factor distinguishing the three locations. Because specific environmental or edaphic variables were not measured and included in the models, the site effect should be interpreted as an overall location effect rather than the effect of quantified environmental factors.

4.4. Correlations Between Traits and Geographic Variables

The correlation analysis between Douglas fir traits and geographic variables indicates several important patterns that align with known provenance–environment relationships. Across all sites, tree volume and basal area were positively correlated, showing that trees with larger diameters also had higher stand productivity [8, 44]. In contrast, tree volume and slenderness index were negatively related, indicating that provenances with higher growth developed stable stems rather than tall and slender ones [42]. Geographic variables also explained some variation. Longitude showed positive correlations with tree volume and basal area, especially at Aleșd and Făget. Elevation of seed origin showed negative correlations with basal area and slenderness index, especially at Aleșd and Făget. Provenances from higher elevations grew more slowly and produced more slender trees [32]. Latitude showed weak effects on growth. Latitude overall was not as reliable a predictor as elevation or the climate of origin. A recent study confirms that adaptive traits in Douglas fir are more closely related to elevation and climate than latitude [6]. The negative correlations between slenderness index and productivity traits (tree volume and basal area) across trials indicate that higher-yielding provenances tended to produce stable stems rather than tall and slender ones.

The correlation analysis suggests that longitude and elevation of origin are the most reliable predictors of Douglas fir performance under Romanian conditions, while latitude plays a secondary role. The role of site-specific conditions and the risk of extreme climatic events must be carefully considered when transferring seed sources across regions. Furthermore, the introduction of Douglas fir requires careful consideration of potential ecological effects, particularly regarding native flora and soil properties [33].

5. Conclusions

This study suggests that both genetic variation (provenance or geographic origin) and environmental conditions (testing site) play important roles in Douglas fir performance in Romania. Since the models relied solely on a categorial site factor, without incorporating explicit environmental or edaphic measurements, the location effect should be understood as a broad site effect.

Provenance significantly influenced tree volume and basal area at two sites, while the slenderness index was influenced by testing site conditions. Strong provenance × location interactions confirmed the importance of genotype – environment relationships.

Interior provenances, such as Idaho, showed stable performance across traits and trials, whereas several coastal provenances showed high productivity at specific trials. Three Romanian provenances, also ranked among the top performers, highlight the adaptive potential of local genetic resources.

The negative correlation between slenderness index and productivity traits suggests that high-yielding provenances tend to produce more stable stems, which may be advantageous under Romanian growing conditions. At the same time, correlations with geographic origin variables underline that both the latitude and elevation of the seed source should be considered in selecting planting material.

Overall, the results emphasise the necessity of matching seed sources to local planting site conditions and demonstrate the importance of maintaining multiple genetic resources for climate adaptation [18] and long-term forest productivity.

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