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Genetic variability of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in provenance trials in Romania

Summary

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The Author

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LIST OF ABBREVIATIONS

DBH – diameter at breast height (1.30 m);

HT – total height;

PH –pruned height;

VOL – mean volume per tree;

SB – basal area;

SF – stem form;

NB – number of branches;

DB – branch diameter;

BA – branch angle;

SV – survival;

FI – forking;

SI – slenderness index;

U.M. – unit of measurement;

ns – not significant;

LRTp – likelihood ratio test for the provenance effect;

Vp – variance of the random effect of provenances;

Vr – residual variance;

MS rep – mean square for replication;

P × L – provenance × location;

MGIDI – Multi-Trait Genotype-Ideotype Distance Index;

MTSI – Multi-Trait Stability Index;

BIO8 – mean temperature of the wettest quarter;

SPI03 – Standardized Precipitation Index (3-month scale);

SPI01 – Standardized Precipitation Index (1-month scale);

SPI09 – Standardized Precipitation Index (9-month scale);

BIO3 – isothermality index;

SPEI06 – Standardized Precipitation Evapotranspiration Index (6-month scale);

SPEI08 – Standardized Precipitation Evapotranspiration Index (8-month scale);

BFFP – frost-free period (days);

BIO6 – minimum temperature of the coldest month;

BIO13 – precipitation of the wettest month;

BIO19 – precipitation of the coldest quarter;

BIO9 – mean temperature of the driest quarter;

SPEI02 – Standardized Precipitation Evapotranspiration Index (2-month scale);

SPEI03 – Standardized Precipitation Evapotranspiration Index (3-month scale);

BIO12 – annual precipitation;

SPEI05 – Standardized Precipitation Evapotranspiration Index (5-month scale);

SHM – Summer Heat Moisture Index;

AHM – Annual Heat Moisture Index;

AIC – Akaike Information Criterion;

VIF – Variance Inflation Factor.

Introduction

Trees play an essential role in terrestrial ecosystems, contributing to ecological balance and human well-being through provisioning and regulating ecosystem services (Negulescu și Ciumac 1959; Beugnon et al. 2025; Waring et al. 2020).

Climate change has led to rising temperatures and an intensification of extreme events, particularly drought, with negative effects on the vitality, productivity, and distribution of forest species, as well as on genetic diversity (IPCC 2022; IPCC 2023). In Romania, an increase in mean temperature is projected, and the adaptive capacity of trees depends on mechanisms such as phenotypic plasticity and the level of genetic diversity, which is essential for ecosystem resilience (Cheval et al. 2017; Dumitrescu și Birsan 2015; Alberto et al. 2013; Bonamour et al. 2019; Kelleher et al. 2015; Alfaro et al. 2014). Climate change will influence physiological processes and the distribution range of species, making it necessary to use provenance trials and select adapted provenances, as well as to introduce alternative species, such as Douglas-fir (Leites și Benito 2023; Moser et al. 2025).

Non-native forest species, introduced in Europe as early as the 17th–18th centuries, currently occupy approximately 4% of the forest area, with Douglas-fir ranking among the most important non-native conifer species (Camenen et al. 2026; van Loo și Dobrowolska 2019). Due to its rapid growth, wood quality, and resistance to stress, Douglas-fir is considered a promising species and an alternative to native species that are more vulnerable to climate change (Kjaer et al. 2014; Bauhus et al. 2013; Ennos et al. 2019; Thurm et al. 2018; Konnert și Bastien 2019).

The research aims to assess the genetic variability of Douglas-fir provenances tested in Romania by analysing growth traits, wood quality, and adaptability to identify high-performing and stable provenances for forest breeding and reforestation programs.

1. CURRENT STATE OF KNOWLEDGE ON DOUGLAS-FIR VARIABILITY IN PROVENANCE TRIALS

1.1. General characterization of Douglas-fir

1.1.1. Brief history

Forest ecosystems in Central Europe have been strongly influenced by human activity since prehistoric times, through the reduction of forested areas and the alteration of species composition in favour of species of high economic value (Essl et al. 2011). The promotion of species such as Norway spruce (*Picea abies*) led to the expansion of its range; however, monocultures have proven vulnerable to disturbance factors such as wind and outbreaks of diseases and pests, highlighting the need to convert them into mixed stands to increase resilience (Carr et al. 2025; Greiser et al. 2025; Štraus și Bončina 2025; Feng et al. 2022).

Modern forest management strategies aim to diversify species composition and, in a controlled manner, introduce allochthonous species better adapted to climate change, characterised by drought tolerance, rapid growth, and high-quality wood (Pötzelsberger et al. 2020). In this context, numerous non-native tree species were introduced into Europe in the 19th and 20th centuries, most of them originating from North America, and they currently occupy approximately 4% of the European forest area (Alizoti et al. 2022; Bindewald 2021; Dimitrova et al. 2022; Schmidt et al. 2016; Brus et al. 2019).

Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] has distinguished itself for its economic and ecological importance, owing to its rapid growth, wood quality, and resistance to biotic and abiotic stresses. (Henin et al. 2019; Remeš et al. 2020; Pâques 2013). The species was discovered in North America at the end of the 18th century and was introduced into Europe in 1827, demonstrating high growth potential that facilitated its subsequent expansion (Menzies 1923; Haralamb 1963; Fletcher și Samuel 2010). Initially used for ornamental purposes, Douglas-fir was later widely planted, including in monocultures, becoming an important species for reforestation in Western Europe (van Loo și Dobrowolska 2019). In Romania, the introduction of Douglas-fir began at the end of the 19th century, and the expansion of plantations continued in the first half of the 20th century, reaching significant areas, especially in Banat, Crișana, and Oltenia, where conditions proved to be favourable (Lăzărescu și Ionescu 1964; Popa-Costea 1973).

1.1.2. Natural and cultivated range

Douglas-fir exhibits the widest latitudinal distribution among commercial conifers in North America, with its range having an inverted "V" shape, reflecting a high adaptability to diverse climatic and ecological conditions (Lavender și Hermann 2014). The western branch corresponds to the coastal variety – *Pseudotsuga menziesii* var. *menziesii*, characterized by rapid growth and adaptation to moist conditions, while the eastern branch corresponds to the interior variety – *Pseudotsuga menziesii* var. *glauca*, adapted to continental climates - Figure 1 (Lavender și Hermann 2014). This distribution highlights the species' ability to occupy a wide range of habitats, from oceanic to continental montane climates (Hermann și Lavender 1990; Lavender și Hermann 2014). The natural range extends over

approximately 18.8 million hectares, the majority of which is located in the United States and Canada (Fletcher și Samuel 2010; Lavender și Hermann 2014).

Douglas-fir was introduced to Europe between 1827 and 1850, initially in the United Kingdom, and then rapidly expanded into numerous European countries in the second half of the 19th century, including Romania (van Loo și Dobrowolska 2019). At present, the species occupies approximately 0.8 million hectares in Europe, being the second most widespread non-native conifer species and used in both pure stands and mixtures (Haralamb 1967; Brus et al. 2019; Ronch et al. 2016).

In Romania, Douglas-fir was introduced in 1887, and a significant expansion of plantations occurred after 1956, with the import of seeds and the implementation of afforestation programs, resulting in over 23,000 hectares planted during 1960–1970 (Popa-Costea 1973; Avram 1960). At present, the area occupied is estimated at approximately 7,300 ha, representing about 0.1% of the national forest fund (INS 2025).

1.1.3. Morphological characteristics

Douglas-fir belongs to the genus *Pseudotsuga*, family Pinaceae, and has an ancient origin, with fossils of the genus dating back to the Oligocene (Stănescu 1977; Stănescu 1979; OECD 2008; Şofletea și Curtu 2007; Schorn și Thompson 1998). In western North America, two main varieties are recognized: the coastal variety (*Pseudotsuga menziesii* var. *menziesii*) and the interior variety (*Pseudotsuga menziesii* var. *glauca*), distinguished by morphological characteristics such as needle color and cone size. (Frothingham 1909; Stănescu 1977; Stănescu 1979; Clinovschi 2005; Șofletea și Curtu 2007).

Douglas-fir is a large coniferous, evergreen species with impressive dimensions, capable of exceeding 80 m in height and 4–5 m in diameter, and often exhibiting a longevity of over 500 years (Ronch et al. 2016; Hermann și Lavender 1990). The stem is straight, with a conical crown in youth that becomes narrower with age, while the bark evolves from smooth and thin to thick and deeply furrowed.

The needles are persistent, flat, and arranged in a single plane, while the pendent cones, with trilobed bracts, represent a distinctive characteristic of the genus (Clinovschi 2005; Franklin et al. 1981). The seeds are winged; maturation occurs in September, and fruiting generally begins between 30 and 40 years of age, being influenced by climatic conditions (Clinovschi 2005; Hermann și Lavender 1990; Șofletea și Curtu 2007). Seed dispersal occurs by wind over relatively short distances (Clinovschi 2005). The root system is relatively shallow compared to other conifers, developing primarily within the organic or upper soil layer (Minore 1979; Peterson și Arbaugh 2011). The wood has medium density and very good mechanical properties, valued for its strength, durability, and elasticity, making it suitable for use in construction and the wood industry.

1.1.3. Ecology of Douglas-fir

Douglas-fir is a species with remarkable ecological adaptability, occupying a wide range of climatic and edaphic conditions within its natural range in North America, from humid maritime to continental montane climates (Fulé și Covington 1999; González-Elizondo et al. 2005; Lavender și Hermann 2014). Climatic differences are determined by latitude, altitude, and distance from the Pacific Ocean, and the interior variety exhibits greater resistance to low temperatures compared to the coastal variety (Hermann și Lavender 1990; Lavender și Hermann 2014). The species is subject to limiting factors such as frost, drought, wind, snow, and fire, among which frost is the most damaging, influencing the distribution and ecological differentiation of the varieties (Hermann și Lavender 1990).

In Europe, Douglas-fir is well adapted to the humid temperate climate, efficiently utilising water and demonstrating good tolerance of summer drought. Studies indicate a relatively low sensitivity to climate change and even a potential for increased productivity (Levanič și Štraus 2022; Nicolescu et al. 2023; Paligi et al. 2024; Huang et al. 2017; Vitali et al. 2018).

In Romania, the species develops optimally in hilly and lower montane areas, at altitudes of up to 800–1,000 m, with moderate moisture requirements and annual precipitation exceeding 600 mm, being more drought-resistant than fir and spruce (Stănescu 1979; Clinovschi 2005; Haralamb 1967; Negulescu și Săvulescu 1957; Purcelean și Pașcovschi 1954; Mihai et al. 2022).

Douglas-fir prefers deep, well-aerated soils with a slightly acidic reaction, but it can grow on a wide variety of soil types due to its tolerance to moisture deficit and low fertility. The main factors influencing productivity are water availability and nitrogen content (Lavender și Hermann 2014; Nicolescu et al. 2023; Čater 2021; Eckhart et al. 2019; Novák et al. 2018; Spellmann et al. 2015).

Altitudinal distribution varies by variety and latitude and is mainly controlled by temperature and moisture. The interior variety occupies higher elevations than the coastal one, and in Europe, the species develops between 300 and 900 m optimally, with extensions up to 1,300–1,600 m in certain regions (Silen 1978; Frothingham 1909; Kirkwood 1922; Costello et al. 2009; Pearson 1931; Nicolescu et al. 2023). In Romania, Douglas-fir exhibits a wide altitudinal range, between 120 and 1,550 m, occurring under diverse temperature and precipitation conditions (Nicolescu et al. 2023; Popa-Costea 1973).

From an ecological perspective, Douglas-fir has moderate shade tolerance, being more tolerant in its early stages but becoming more light-demanding with maturation. Optimal regeneration occurs under conditions of moderate light and reduced canopy cover (Hermann și Lavender 1990; Nicolescu et al. 2023; Schütz et al. 2015; Thomas et al. 2022; Frei et al. 2022; Stokes et al. 2020).

1.1.4. Importance of the species

Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) is a valuable forest species, characterised by rapid growth, ecological adaptability, and high-quality wood, being considered a promising substitute for

native conifers affected by climate change (Pâques 2013; Ronch et al. 2016; Konnert și Bastien 2019; Drewett 2015; Rais et al. 2014; Podrázský et al. 2020). Due to its high productivity and superior physico-mechanical properties, Douglas-fir wood often exceeds spruce and pine in density and strength, and is comparable to larch. (Zeidler et al. 2022; Giagli et al. 2019; Pollet et al. 2017). It is widely used in construction and the wood industry, in the form of sawn timber, beams, panels, sleepers, joinery elements, and other products, due to its mechanical strength, durability, and dimensional stability (Pâques 2013; Ross 2021).

The species also contributes to the improvement of soil characteristics and forest ecosystems, being drought-resistant and capable of achieving superior growth compared to other species, with increases of 15–50% higher than those of spruce and beech, and even greater compared to pine and oak (Kupka et al. 2013; Podrázský et al. 2014; Podrázský et al. 2016; Podrázský et al. 2020; Eilmann și Rigling 2012; Montwé et al. 2015; Konnert et al. 2019). From an economic perspective, Douglas-fir wood is marketed at higher prices than other European conifers, on average approximately 25% more expensive than spruce, highlighting its importance in the European forestry sector (Henin et al. 2019; Pulkrab et al. 2014; Experts Forestiers de Belgique 2022).

1.2. Genetic variability of Douglas-fir in provenance trials

1.2.1. Provenance trials

There are two main methods for separating genetic influences from environmental ones: provenance trials and molecular genetic techniques. Provenance trials involve cultivating genetic material originating from different provenances, progenies, or clones under similar environmental conditions, so that the observed differences can be attributed to genetic factors (White et al. 2007). Provenance refers to the geographic origin of the seeds, while progenies and clones result from sexual or vegetative reproduction, thereby allowing the transmission of the genotype (Breed et al. 2018; Enescu 1973).

The main objective of provenance trials is to separate the genetic component from the environmental one and to identify valuable seed sources. The traits analysed are generally quantitative, polygenically controlled, and influenced by genotype × environment interaction (Enescu 1973; Enescu 1982). These traits can be classified according to their mode of quantification, adaptive value, environmental dependence, and genetic control (White et al. 2007).

Provenance trials allow evaluation of provenance performance in relation to environmental factors and are essential for understanding genetic variability and the adaptation of forest species. Since direct observations in natural populations are limited, controlled experiments provide a solid basis for estimating genetic influences and for supporting silvicultural practices (White et al. 2009; Bailey et al. 2021). These studies contribute to the analysis of phenotypic plasticity, adaptation, and responses to climatic conditions, being used for the selection of valuable provenances and the optimization of forest management (Schwinning et al. 2022). Research on provenances has a history of over 260 years, with the first experiments conducted in France in the 18th century (Matyas 1994; FAO 2025; Langlet 1971).

At present, provenance trials are used to study local adaptation, ecotypes, adaptive potential, phenotypic plasticity, genotype × environment interaction, growth stability, genetic parameters, and the selection of superior provenances, as well as to assess the impact of climate change and to guide forest management (Halbritter et al. 2018; McDonough MacKenzie et al. 2018; Korecký et al. 2021; Peuke et al. 2002; Chauvin et al. 2019; Mihai et al. 2018; Čortan et al. 2019; Mátyás et al. 2023; Mihai et al. 2022; Poupon et al. 2023; Di Fabio et al. 2024; Hayatgheibi et al. 2019; Zhang et al. 2022; Kurjak et al. 2024; Nabais et al. 2018; Park și Rodgers 2023).

1.2.2. Douglas-fir provenance trials worldwide

The first studies on the geographic variation of Douglas-fir were conducted in the Pacific Northwest and were followed by the first "common garden" experiments initiated in 1912, which highlighted genetic differences among coastal populations (Lavender și Hermann 2014; Silen 1978). Subsequent studies confirmed the existence of geographic variation and the differences between the coastal and interior varieties, with the former being more productive and the latter more resistant to harsh climatic conditions. (Ching 1965; White și Ching 1985; Gamble et al. 1996).

Extensive testing programs, including those in Canada and those initiated by the British Columbia Forest Service, have highlighted the high genetic variability and ecotypic differentiation of the species (Illingworth și St. Pierre 1975; Ying 1990). Aceste rezultate au stat la baza programului internațional IUFRO, început la sfârșitul anilor 1960, care a urmărit evaluarea globală a proveniențelor și standardizarea metodologiei experimentale (Lavender și Hermann 2014; Fletcher și Barner 1978).

Within the IUFRO program, 182 provenances from across the entire natural range were tested using a common experimental design, with periodic measurements of growth, survival, and resistance to climatic factors (Enescu 1984; Fletcher și Barner 1987; Lavender și Hermann 2014). The results highlighted the superiority of coastal provenances under oceanic conditions and of interior provenances under continental conditions, as well as the existence of clinal patterns of genetic variation (Fletcher și Barner 1987). Based on these studies, recommended provenance zones were established for different regions, and the inappropriate use of certain seed sources led to suboptimal performance in plantations (Lavender și Hermann 2014; Konnert et al. 2019).

At the European level, numerous countries have participated in provenance testing and breeding programs. In general, the results have indicated superior performance of local populations or of coastal provenances from Washington and Oregon, depending on the specific climatic conditions of each region (Pâques 2013; Thompson și Pfeifer 1995; Ducci et al. 2003; Mejnartowicz și Szmidt 1978; Mejnartowicz 1976; Merlo 2002; Fletcher și Samuel 2010). These studies have contributed significantly to the development of genetic improvement programs, the selection of adapted provenances, and the establishment of strategies for the use of forest reproductive material in Europe.

1.2.3. Douglas-fir provenance trials established in Romania

In Romania, the first nursery tests for Douglas-fir included 61 provenances from the natural range and from European plantations, and the material was used to establish five provenance trials between 1977 and 1980 to evaluate adaptability, growth, and wood quality (Enescu, 1984). At present, only three of these trials still exist.

Results at 18 years indicated good adaptation of provenances from Idaho and western Washington, as well as Romanian artificial provenances, as reflected by high survival values (Moise, 1998). The best growth performance was recorded for provenances from Washington and Oregon, particularly from low-altitude areas, although local provenances also showed favourable results (Moise, 1998). The analysis revealed significant genetic variability and important genotype × environment interactions, with coastal provenances generally exhibiting superior performance, though not across all testing conditions.

Following the initial stage of introduction and testing, no genetic improvement program for Douglas-fir was further developed in Romania. The present study aims to relaunch this program by capitalising on the existing provenance trials and applying modern multivariate selection methods to initiate a new breeding cycle and establish seed orchards.

2. AIM AND OBJECTIVES

The aim of the research presented in this doctoral thesis is to assess the genetic variability of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] based on the results obtained from provenance trials in Romania, in order to select the most productive and well-adapted provenances in the context of projected climate change.

The specific objectives are:

1. To evaluate the interpopulation genetic variability of Douglas-fir provenances in relation to the main quantitative, wood quality, and adaptive traits;

2. To identify provenances with superior performance and high adaptability, in order to propose them as tested seed sources in Romania;

3. To assess genotype × environment interactions and the spatio-temporal stability of Douglas-fir provenance performance;

4. To select provenances with high and stable performance to serve as genetic resources for breeding and afforestation programs, using the multivariate selection indices MGIDI and MTSI;

5. To analyse phenotypic correlations among the main traits studied;

6. To analyse the relationships between the studied traits and geographic gradients, as well as with climatic variables at the place of origin;

7. To analyse the relationship between Douglas-fir provenance performance and the climatic differences between the place of origin and the test site, using response and transfer functions.

3. MATERIAL AND METHODS

3.1. Description of the studied provenance trials

Of the five Douglas-fir provenance trials established in Romania, only three are currently still in existence, located at Aleșd (Bihor County), Făget (Timiș County), and Padeș (Gorj County), all established in 1977, while those at Bocșa Montană and Târgu Lăpuș have been dismantled (Figure 2B). The experimental design is a partially balanced square lattice of type 8 × 8, with three replications; each experimental plot contains 25 seedlings planted at 2 m spacing.

The tested provenances originate from the USA, Canada, Europe, and Romania, covering a wide range of latitudinal, longitudinal, and altitudinal variability (Figure 1; Figure 2A; Figure 2B). In total, 55 provenances were tested at Aleșd, 49 at Făget, and 48 at Padeș, of which 38 are common across all three locations (Table 2).

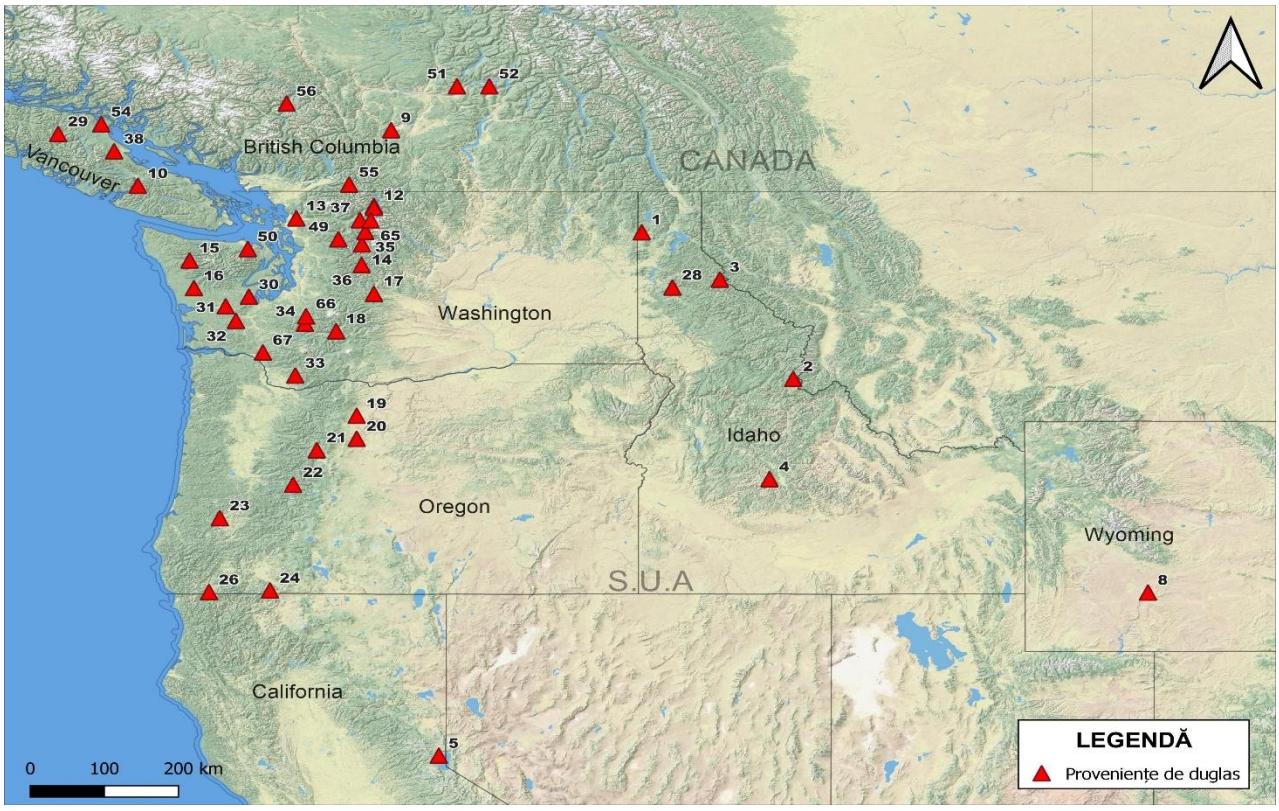

Fig. 1 Origin of Douglas-fir provenances from the USA and Canada tested in Romania

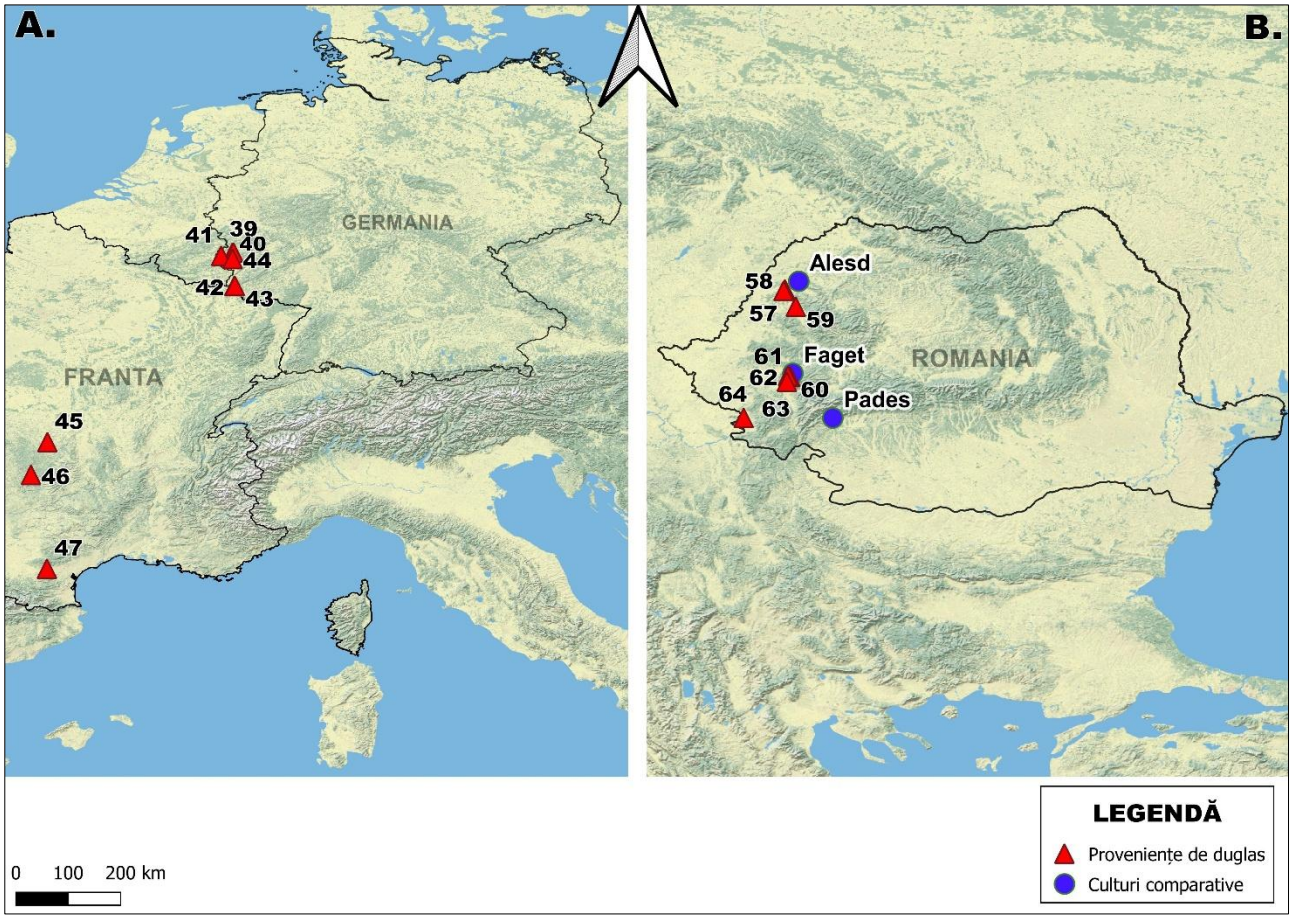

Fig. 2 Location of Douglas-fir provenances from Germany and France – panel A, and of the provenances tested in Romania – panel B.

Tab. 1 Douglas-fir provenance trials established in 1977

Trial	Aleșd	Făget	Padeș
Site quality	5242 – Hilly beech forest (Bm), medium edaphic eutricambisol with *Asperula–Asarum*	6153 – Hilly oak stands with mixed broadleaved forests without beech, Bs/m, luvosol and greic phaeozem, high edaphic potential	5243 – Hilly beech forest (Bs), eutricambisol with high edaphic potential, with *Asperula–Asarum*
Forest type	4214 – Hilly beech forest with mull flora, medium productivity	5111 – Typical sessile oak stand with mull flora (s)	4211 – Hilly beech forest with mull flora (s)
Soil type	3101 – Typical eutricambisol	2201 – Typical luvosol	3101 – Typical eutricambisol

Region of provenance	E2 – Western Apuseni Mountains	D2 – Banat Mountains: Țarcu – Poiana Ruscă	C2 – Southern Southern Carpathians
Slope (°)	15	26	25
Site exposure	V	E	SE
Altitude (m)	670	330	720
Lat N	47.15°	45.76°N	45.09°
Long E	22.33°	22.29°	22.89°
Mean annual temperature (°C) **1977-2023**	5,5	10,4	7,8
Mean temperature during the growing season (°C) **May–September**	15,3	17,9	15,4
Mean annual precipitation (mm) 1977–2023	860	852	975
Mean precipitation during the growing season (mm) **May–September (1977–2023)**	450	455	502

Tab. 2 Douglas-fir provenances tested in the three provenance trials

No.	Prov. code	Provenance	Country/State	Lat. N	Long. E	Altd. (*m*)
1	**1**	Idaho (var. *glauca*)	SUA	48°00′	-116°95′	780
2	**2**	Idaho (var. *glauca*)	SUA	47°48′	-113°61′	1389
3	**3**	Idaho (var. *glauca*)	SUA	47°52′	-115°68	1356
4	**4**	Boise (var. *glauca*)	SUA	44°00′	-115°00′	1829
5	**5**	El Dorado	SUA, California	39°17′	-120°08′	1387
6	**8**	South End Pass	SUA, Wyoming	50°07′	-120°85′	900
7	**9**	Merrit	Canada, British Columbia	50°04′	-120°51′	900
8	**10**	Franklin River	Canada, British Columbia	49°06′	-124°46′	150
9	**11**	Duncan	Canada, British Columbia	48°75′	-121°17′	450
10	**12**	Diablo Dam – Whatcom	SUA, Washington	48°72′	-121°17′	450
11	**13**	Skagit – Sedro Wooley	SUA, Washington	48°53′	-122°31′	60
12	**14**	Snohomish -Sloan Creek	SUA, Washington	48°08′	-121°18′	650
13	**15**	Jefferson – Hoh River	SUA, Washington	47°48′	-123°58′	240
14	**16**	Grays Harbour – Humptulips	SUA, Washington	47°19′	-123°54′	140
15	**17**	Kittias – CleElum	SUA, Washington	47°13′	-121°07′	640
16	**18**	Lewis – Packwood	SUA, Washington	46°34′	-121°42′	300
17	**19**	Pine Grove	SUA, Oregon	45°06′	-121°23′	730
18	**20**	Benton – Corvallis,	SUA, Oregon	44°42′	-121°23′	76
19	**21**	Marion Forks	SUA, Oregon	44°30′	-122°00′	1060
20	**22**	Lane – Oakridge	SUA, Oregon	43°54′	-122°22′	880

21	**23**	Rosenburg	SUA, Oregon	43°19′	-123°30′	280
22	**24**	Jakson – Ashland	SUA, Oregon	42°05′	-122°39′	1500
23	**26**	Siskiyou – Hawkinsville,	SUA, California	41°47′	-123°40′	1060
24	**28**	Chatcolet, S. (var. *glauca*)	SUA, Idaho	47°20′	-116°30′	700
25	**29**	Vancouver	Canada, British Columbia	50°00′	-126°00′	150
26	**30**	Hoodsport	SUA, Washington	47°10′	-123°03′	300
27	**31**	Elma	SUA, Washington	47°00′	-123°30′	300
28	**32**	Pe Ell-Sand Creek, Mc. Donald	SUA, Washington	46°45′	-123°15′	200
29	**33**	Yacolt – Spotted Deernt – Battle G.	SUA, Washington	45°48′	-122°20′	600
30	**34**	Vicinity, Mineral Walker Road	SUA, Washington	46°40′	-12°15′	500
31	**35**	Darrington – Texas Pond	SUA, Washington	48°18′	-121°15′	280
32	**36**	Skycomish – Beckler Peak	SUA, Washington	47°42′	-121°20′	500
33	**37**	Concrete – Presentin Creek	SUA, Washington	48°30′	-121°20′	110
34	**38**	Oyster R.	Canada, British Columbia	49°42′	-125°08′	400
35	**39**	Daun Ost – Abt. 39 A – Rezervație	Germany	50°12′	06°50′	520
36	**40**	Daun Ost – Abt. 46 C.	Germany	50°11′	06°52′	500
37	**41**	Prüm Süd – Abt. 79 C	Germany	50°13′	06°25′	380
38	**42**	Wittlich West – Abt. 3B	Germany	49°47′	06°54′	230
39	**43**	Wittlich West – Abt. 1B	Germany	49°47′	06°55′	230
40	**44**	Manderscheid – Abt. 36	Germany	50°06′	06°50′	400
41	**45**	Poinsat – Puy de Dome	France	46°04′	02°43′	750
42	**46**	Les Farges III	France	45°32′	02°07′	665
43	**47**	Moussans II	France	43°26′	02°42′	750

44	**49**	Darrington III	SUA, Washington	48°10′	-121°40′	200
45	**50**	Clallam Country – Louella	SUA, Washington	48°00′	-123°04′	330
46	**51**	Pinetan	Canada, British Columbia	50°50′	-119°50′	830
47	**52**	Shuswape Lake	Canada, British Columbia	50°50′	-119°20′	530
48	**54**	Morton Lake	Canada, British Columbia	50°10′	-125°20′	150
49	**55**	Centre Creek – Chilliwack Valley	Canada, British Columbia	49°07′	-121°30′	460
50	**56**	Devine – Dist.	Canada, British Columbia	50°32′	-122°28′	380
51	**57**	Pădurea Neagră	Romania	47°03′	22°17′	500
52	**58**	Piatra Albă	Romania	47°01′	22°15′	580
53	**59**	Toplița	Romania	46°46′	22°20′	330
54	**60**	Aninoasa Mare	Romania	45°43′	22°15′	550
55	**61**	Vârful Dăii	Romania	45°44′	22°13′	825
56	**62**	Vârful Dăii	Romania	45°44′	22°13′	420
57	**63**	Nădrăgel	Romania	45°43′	22°13′	560
58	**64**	Anina – Buhui	Romania	45°10′	21°55′	650
59	**65**	Sedro Woolley	SUA, Washington	48°30′	-122°10′	720
60	**66**	Elbe	SUA, Washington	46°50′	-122°10′	720
61	**67**	Kelso	SUA, Washington	46°12′	-122°50′	609

3.2. Climatic regime of the test sites

In the Aleșd comparative trial, the mean annual temperature is 5.5 °C and the total annual precipitation amounts to 860 mm, with a maximum occurring between May and July; in the Făget comparative trial, the mean annual temperature is 10.4 °C and the total annual precipitation is 852 mm, with a peak between April and July; while in the Padeș comparative trial, the mean annual temperature is 7.8 °C and the total annual precipitation reaches 975 mm, with a maximum between April and July (Tabel 1).

3.3. Measurement and observations

The measurements and observations were carried out in 2024, 47 years after the establishment of the provenance trials, analysing quantitative, wood quality, and adaptive traits.

The analysed traits were classified as follows:

I. **QUANTITATIVE TRAITS:** diameter at 1.30 m (DBH), total height (HT), tree volume (VOL), basal area (SB).

II. **WOOD QUALITY TRAITS:** height to the first green or pruned height (PH), stem form (SF), number of branches (NB), branch diameter (DB), branch insertion angle (BA), and forking (FI).

III. **ADAPTIVE TRAITS:** survival (SV), slenderness index (SI).

The methodology for evaluating quantitative, wood quality, and adaptive traits was adopted and adapted from the TreeBreedex (TreeBreeding for Resilience and Efficiency) protocol (Fulvio Ducci et al. 2012).

Tab. 3 Methodology for evaluating quantitative, wood quality, and adaptive traits

Trait	U.M./Index	Measuring instrument/Index description
i. QUANTITATIVE TRAITS		
DBH	*cm*	Haglöf calliper (± 0,1 cm)
HT	*m*	Vertex IV (± 0,1 m)
VOL	m^3	Equation 5
SB	$m^2\ ha^{-1}$	Equation 6
ii. WOOD QUALITY TRAITS		
PH	*m*	Vertex IV (± 0,1 m)
SF	5	Straight stem, without curvature

	4	Relatively straight stem (slight curvature, 1–2 bends)
	3	Slight to moderate curvature in different directions (≥ 3 bends)
	2	Moderate to pronounced curvature (1–2 bends)
	1	Highly curved stem (≥ 3 severe bends)
NB	Number of branches in the first green whorl	
DB	1	Branch diameter < 2 cm
	2	Branch diameter 2-5 cm
	3	Branch diameter > 5 cm
BA	1	Angle < 90°
	2	Angle ≃ 90°
	3	Angle > 90°
FI	4	Not forked
	3	Forked in the upper third
	2	Forked in the middle of the stem
	1	Forked in the lower third
iii. ADAPTIVE TRAITS		
SV	Percentage of living trees out of the 25 initially planted per provenance	
SI	%	Equation 7

Note: *U.M. – unit of measurement; DBH – diameter at 1.30 m; HT – total height; VOL – mean tree volume; SB – basal area; PH – pruned height; SF – stem form; NB – number of branches; DB – branch diameter; BA – branch insertion angle; FI – forking; SV – survival; SI – slenderness index.*

3.4. Statistical analyses

The analysis of genetic variability for each trait was performed for each provenance trial and across all trials.

1. Analysis of genetic variability at the trial level

At the level of each trial (Aleșd, Făget, and Padeș), the aim was to highlight differences among provenances and to estimate their variance using a linear mixed model, adapted from Nanson (2004), in which provenance was treated as a random factor and replication as a fixed factor.

$$\boldsymbol{Y_{ijk} = \mu + P_j + R_k + P_j \times R_k + e_{ijk}} \qquad (1)$$

where:

Y_{ijk} is the observed value of traits (DBH, TH, VOL, SB, PH, SF, NB, DB, BA, FI, SV, SI),

μ is the overall mean,

P_j is the effect of the *j* - th provenances,

R_k is the effect of the *k* - th replication,

$P_j \times R_k$ is the provenance × replication interaction,

e_{ijk} is the residual error associated with tree *ijk*.

2. Analysis of genetic variability across trials

In addition to the separate evaluation at each test site, an analysis was also performed across the three test sites (Aleșd, Făget, and Padeș). The aim of this analysis was to highlight genetic variability among provenances and to estimate the impact of the provenance × site interaction on the analyzed traits (Nanson 2004).

For this analysis, a linear mixed model was used, in which the effect of provenance, as well as the provenance × trial interaction, was considered a random factor, while the effect of trial was treated as a fixed factor:

$$\boldsymbol{Y_{ijk} = \mu + C_i + P_j + R_k + C_i \times P_j + e_{ijk}} \qquad (2)$$

where:

Y_{ijk} is the observed value of the traits (DBH, TH, VOL, SB, PH, SF, NB, DB, BA, FI, SV, SI),

μ is the overall mean,

C_i is the effect of the *i* - th trial,

P_j is the effect of the *j* - th provenance,

R_k is the effect of the *k* - th replication,

$C_i \times P_j$ is the provenance × trial interaction,

e_{ijk} is the residual error associated with tree *ijk*.

This analysis was essential, as it enabled both the separation of variance attributable to genetic and environmental factors and the evaluation of their interactions. The analysis of genetic variability across provenance trials was conducted using the 38 provenances common to all sites.

The calculation of linear mixed models, as well as the testing of the significance of the included effects, were performed using the *lmer* package (Kuznetsova et al. 2020) in the R software environment (R Core Team 2024).

3. Multivariate selection indices (MGIDI and MTSI)

To evaluate the performance and stability of Douglas-fir provenances, two multivariate selection indices recently introduced in tree breeding programs were used:

i) **MGIDI** (Multi-Trait Genotype–Ideotype Distance Index) (Olivoto and Nardino 2021) – applied in each provenance trial, to select provenances with superior performance relative to an ideal genotype (ideotype).

ii) **MTSI** (Multi-Trait Stability Index) (Olivoto et al. 2019) – applied across all test sites to assess the performance and stability of provenances under different ecological conditions.

3.1. MGIDI calculation

MGIDI was calculated through the following steps:

1. *Trait rescaling* – all traits were rescaled to a common 0–100 scale. For traits to be maximized, the maximum value was transformed to 100 and the minimum to 0. For traits to be minimised, the transformation was reversed so that the minimum value was assigned a score of 100 and the maximum a score of 0.

2. *Factor analysis* – based on the transformed values, a factor analysis was performed to group correlated traits into common factors and to estimate factor scores for each provenance. This step reduces dimensionality and minimises the effect of collinearity among traits.

3. *Ideotype definition* – a hypothetical genotype (ideotype) was defined, characterised by a score of 100 for all analysed traits, representing the ideal model toward which selection is directed.

4. *Distance calculation* – for each provenance, the Euclidean distance from the ideotype was calculated, resulting in the MGIDI index. Provenances with lower values of this index were considered closer to the ideotype and, therefore, more valuable for selection.

The equation used is as follows:

$$\boldsymbol{MGIDI_i} = \left[\sum_{\boldsymbol{j=1}}^{\boldsymbol{f}} \left(\boldsymbol{y_{ij}} - \boldsymbol{y_j}\right)^{\boldsymbol{2}}\right]^{\boldsymbol{0.5}} \qquad (3)$$

where:

$MGIDI_i$ = the genotype–ideotype distance index for provenance *i*,

yij = the score of provenance *i* for factor *j*,

yi = the score of the ideotype for factor *j*,

f = the number of extracted factors.

The selection intensity for MGIDI was set at 20%, corresponding to selecting 11 provenances from the Aleșd trial (55 tested), 10 from the Padeș trial (48 tested), and 10 from the Făget trial (49 tested).

The lower the MGIDI value associated with a provenance, the closer it is to the defined ideotype and, consequently, the closer its trait values are to the targeted objectives. In this way, the index enables the ranking of provenances by simultaneously integrating information from multiple traits and reducing the risk that a single variable influences selection. Provenances with low MGIDI values can be considered candidate genotypes for use in breeding programs and for recommendations regarding forest reproductive material.

3.2. MTSI calculation

MTSI was calculated through the following steps:

1. *WAASB calculation (Weighted Average of Absolute Scores*) – used to determine the stability of the 38 provenances common across the three test sites, based on linear mixed models. WAASB values and the values of the analysed traits were rescaled to a common 0–100 scale.

2. *WASBY index calculation* – which combines stability (WAASB) and mean performance (Y) of the provenances. The selection intensity was set at 20%.

3. *Ideotype definition* – similar to MGIDI, but in this case, the ideotype was defined by the maximum score (100) for both performance and stability.

4. *Euclidean distance calculation* – for each provenance, the distance to the ideotype was estimated, the result representing the MTSI value:

$$\boldsymbol{MTSI_i} = \left[\sum_{\boldsymbol{j=1}}^{\boldsymbol{f}} (\boldsymbol{F_{ij}} - \boldsymbol{F_j})^{\boldsymbol{2}}\right]^{\boldsymbol{0.5}} \qquad (4)$$

where:

$MTSI_i$ = the multi-trait stability index for provenance *i*,

F_{ij} = the score of provenance *i*,

Fj = the score of the ideotype,

f = the number of extracted factors.

Thus, provenances with lower MTSI values are considered closest to the ideotype, indicating an optimal balance between performance and stability.

The calculations for determining the MGIDI and MTSI indices were performed in R using the metan package (Olivoto and Lúcio 2020).

Correlations among quantitative, wood quality, and adaptive traits, as well as their relationships with geographic provenance gradients, were evaluated using the Pearson correlation coefficient within each provenance trial. This analysis assumes a distribution as close as possible to normality and quantifies the strength of relationships on a scale ranging from -1 (negative correlation) to +1 (positive correlation), with 0 indicating the absence of a linear association. Correlation matrices were graphically illustrated using correlograms generated with the corrplot package (Wei and Simko 2021) in R.

Geographic variables—latitude (°N), longitude (°E), and altitude (m above sea level)—were determined from the provenance coordinates. Climate diagrams for the provenance trials, corresponding to the period 1977–2023, were generated using the climatol package (Guijarro and Guijarro 2019) in R.

The following regression equation was used to calculate **tree volume** (Giurgiu 2004):

$$\log v = a_0 + a_1 \log d + a_2 log^2 d + a_3 \log h + a_4 \log_2 h \qquad (5)$$

where:

d = tree diameter at breast height (*cm*);

h = tree height (*m*);

v = tree volume (m^3).

The regression coefficients used in Equation 5 are those corresponding to Douglas-fir:

a_0 = -4,29910;

a_1 = 1,90710;

a_2 = 0,02841;

a_3 = 1,01819;

a_4 = -0,055894.

Basal area (m^2) was calculated at the tree level using Equation 6:

$$SB = \frac{\pi}{4} \times \mathbf{DBH^2} \quad (6)$$

where:

DBH = diameter at 1.30 m;

- individual values were summed to determine basal area at the provenance level;

- provenance-level values were subsequently expressed per hectare (m^2ha^{-1}).

The slenderness index (*%*) was calculated at the tree level using Equation 7 (Nicolescu 2016):

$$SI = \frac{HT}{DBH} \times 100 \quad (7)$$

where:

HT = total height (*m*);

DBH = diameter at 1.30 m.

Response and transfer functions were developed using multiple regression models, including linear and quadratic terms for climatic variables (Wang et al. 2006). The general model had the following form:

$$z = a + b \cdot x^2 + c \cdot y$$

where:

z = the analyzed trait (DBH, HT, SV);

a, b, c = regression coefficients;

x, y = climatic variables.

Response functions describe the relationship between provenance performance and the climatic variables of the place of origin, while transfer functions quantify the effect of climatic differences between the provenance origin and the test sites on the analysed traits (Wang et al. 2006).

The steps for constructing the *transfer functions* were as follows:

1. The analysis was performed only on provenances from the USA present at each test site (Aleșd, Făget, and Padeș).
2. For each provenance, the climatic parameters of the place of origin were extracted from the ClimateDT database (Marchi et al. 2024) for the period 1901–1977, while for each trial, the climate of the test site was characterised using climatic variables corresponding to the period 1977–2023.

3. Transfer variables were calculated as the difference between the climate of the test site and the climate of the provenance origin:

$$\Delta C = C_{test} - C_{origin}$$

4. Candidate variables were subjected to univariate screening (Zuur et al. 2010), and predictor selection was based on the statistical significance of the correlation coefficients (R^2) ($p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$), the Akaike Information Criterion (AIC) (Akaike 1974), and the absence of collinearity among predictors, assessed using the Variance Inflation Factor (VIF) (Craney and Surles 2002; Thompson et al. 2017).

5. For each trait (DBH, HT, and SV), multiple regression models with linear terms were initially fitted. Subsequently, the optimal model form was evaluated by testing the inclusion of second-order (quadratic) terms for the selected climatic variables. The quadratic nature of the model was confirmed when the squared term significantly improved model fit, as assessed by AIC, an increase in the adjusted coefficient of determination (R^2adj), and the statistical significance of the coefficients, while maintaining low collinearity among predictors (VIF).

6. The following relationship defines the final transfer functions (Wang et al. 2006):

$$z = a + b \cdot \Delta x + c \cdot (\Delta x)^2 + d\Delta y + \varepsilon$$

where:

z = the analyzed trait (DBH, HT și SV);

Δx, Δy = climatic transfer distances;

a, b, c, d = regression coefficients;

ε = residual error.

7. The models were used to highlight the effects of climatic transfer on provenance performance.

For the *response functions*, the same methodological steps described above were followed, with the following differences:

Climatic predictors were defined based on variables characterising the climates of the places of origin.

1. The models described the direct relationship between provenance performance at each test site and the climate of the place of origin, without analysing the effect of climatic differences between origin and test site.

2. Following multivariate analysis, climatic predictors were selected for each analysed trait, and the final response functions were defined using models with one or two predictors, including linear terms and, where appropriate, quadratic terms. Statistical analyses and graphical representations were performed in R, using the *car* package (Fox and Weisberg 2019) and *ggplot2* (Wickham 2016).

4. RESULTS AND DISCUSSION

4.1. Genetic variability of quantitative traits in each provenance trial

The analysis of data obtained nearly five decades after the establishment of the provenance trials revealed significant differences among the Douglas-fir provenances tested in Romania. The results reflect both genetic and environmental effects, highlighting how Douglas-fir provenances respond differently to local conditions (Table 4).

Tab. 4 Results of the linear model for the quantitative traits analysed in each provenance trial

Trial	Trait	LRTp	Vp	Vr	MS rep	Mean ± SD
Aleșd	DBH	23.16 ***	7.23 (11%)	60.77 (89%)	80.66 ^{ns}	35.9 ± 8.18
	HT	29.67 ***	3.36 (15%)	19.68 (85%)	13.32 ^{ns}	30.2 ± 4.71
	VOL	18.53 ***	0.06 (10%)	0.57 (90%)	0.25 ^{ns}	1.43 ± 0.78
	SB	19.27 ***	2.42 (10%)	21.11 (90%)	20.11 ^{ns}	51.2 ± 4.79
Făget	DBH	8.27 **	2.87 (5%)	56.16 (95%)	565.59 ***	28.8 ± 7.75
	HT	12.80 ***	2.01 (8%)	24.73 (92%)	923.91 ***	29.6 ± 5.31
	VOL	9.07 **	0.01 (3%)	0.34 (97%)	5.65 ***	0.93 ± 0.60
	SB	8.92 **	0.68 (5%)	12.07 (95%)	131.31 ^{ns}	34.8 ± 3.68
Padeș	DBH	2.89 ^{ns}	1.93 (4%)	50.89 (96%)	0.31 ^{ns}	34.7 ± 7.25
	HT	18.97 ***	1.59 (9%)	15.29 (91%)	20.03 ^{ns}	28.8 ± 4.1
	VOL	6.57 *	0.21 (37%)	0.36 (63%)	0.05 ^{ns}	1.29 ± 0.62
	SB	3.30 ^{ns}	0.63 (4%)	15.69 (96%)	0.31 ^{ns}	42.7 ± 4.03

Note: *Significance levels: p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); ns – not significant (p > 0.05); LRTp – likelihood ratio test for the provenance effect; Vp – variance of the random provenance effect; Vr – residual variance; MS rep – mean square for replication; DBH – diameter at 1.30 m; HT – total height; VOL – tree volume; SB – basal area.*

In the Aleșd provenance trial, the effect of provenance was highly significant for all analysed traits (DBH, HT, VOL, SB), explaining 10–15% of the total variance, while residual variance accounted for 85–90%. The effect of replication was not significant (p > 0.05).

In the Făget provenance trial, provenance had a significant effect on DBH, VOL, and SB, and a highly significant effect on HT, accounting for 3–8% of the total variance, with the remainder explained by

residual variance (92–97%). The effect of replication was significant for DBH, HT, and VOL, but not significant for SB.

In the Padeș provenance trial, provenance was not significant for DBH and SB but was significant for HT and VOL, accounting for 4–37% of the total variance, while residual variance accounted for 63–96%. The effect of replication was not significant for any of the traits.

4.1.1. Diameter at 1.30 m (DBH)

The mean DBH values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 3.

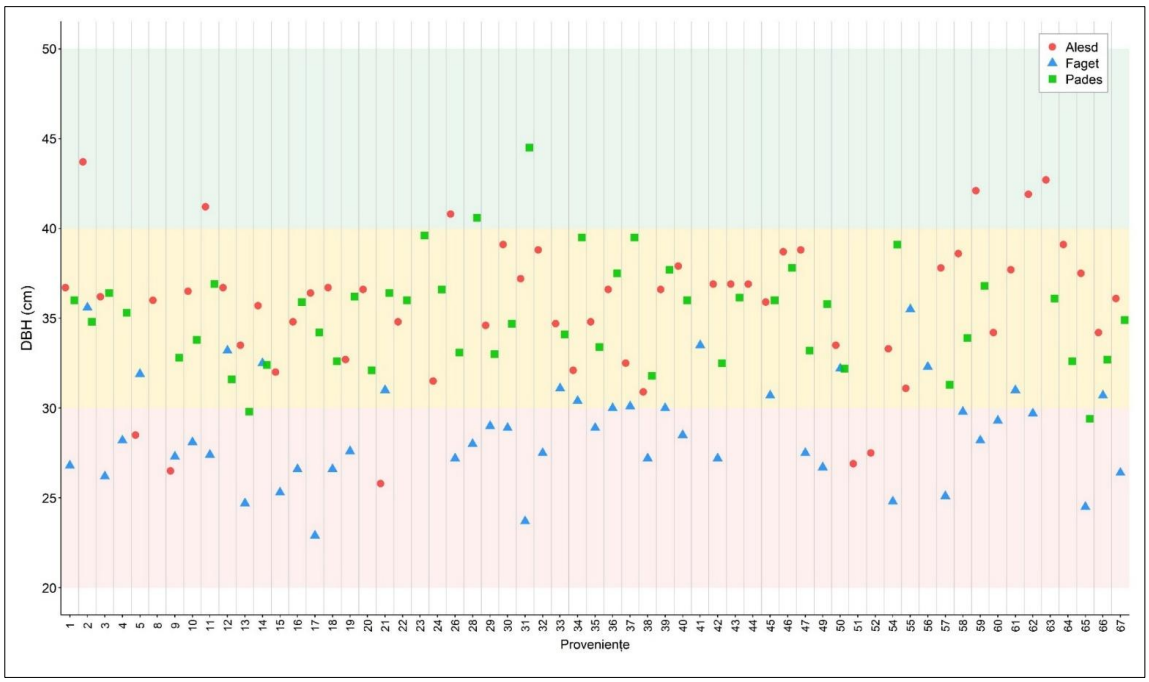

Fig. 3 Variation in diameter at 1.30 m of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, based on DBH performance, the top-ranked provenances were: 2 – Idaho (var. *glauca*), USA; 63 – Nădrăgel, RO; 59 – Toplița, RO; 62 – Vârful Dăii, RO and 11 – Duncan, CA. The lowest DBH performances were recorded for: 21 – Marion Forks, USA; 9 – Merrit, USA and 51 – Pinetan, CA (Figure 3).

In the Făget comparative trial, the top DBH performers were: 2 – Idaho (var. glauca), USA; 55 – Centre Creek – Chilliwack Valley, CA; 41 – Prüm Süd – Abt. 79 C, DE; 12 – Diablo Dam – Whatcom, USA and 14 – Snohomish – Sloan Creek, USA. The lowest performances were: 17 – Kittitas – Cle Elum, USA; 31 – Elma, USA and 65 – Sedro-Woolley, USA (Figure 3).

In the Padeș comparative trial, the top DBH provenances were: 31 – Elma, USA; 28 – Chatcolet, S. (var. *glauca*), USA; 23 – Rosenburg, USA; 34 – Vicinity, Mineral Walker Road, USA and 37 – Concrete – Presentin Creek, USA. The lowest DBH performances were recorded for: 65 – Sedro Wooley, USA; 13 – Skagit – Sedro Wooley, USA and 57 – Pădurea Neagră, RO (Figure 3).

In terms of mean DBH at the trial level, the highest value was recorded at Aleșd (35.9 cm), followed by Padeș (34.7 cm), while Făget ranked last with 28.8 cm.

4.1.2. Total height (HT)

The mean HT values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 4.

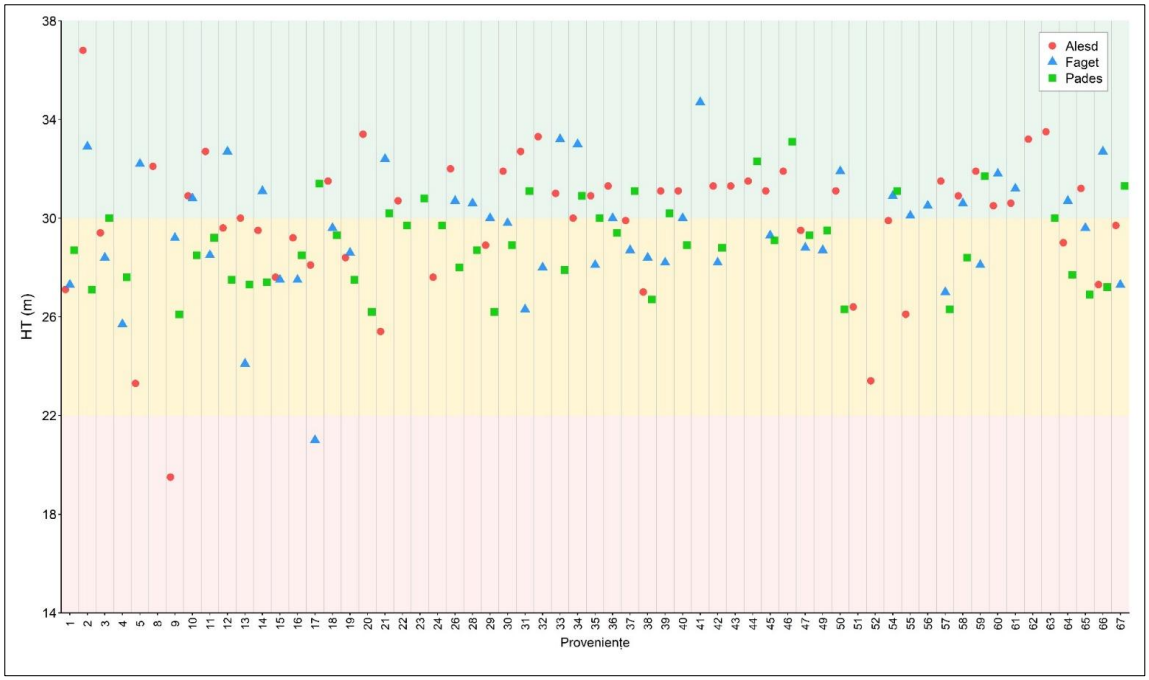

Fig. 4 Variation in total height of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, based on HT performance, the top-ranked provenances were: 2 – Idaho (var. *glauca*), USA; 63 – Nădrăgel, RO; 20 – Benton – Corvallis, USA; 32 – Pe Ell – Sand Creek, Mc. Donald, USA and 62 – Vârful Dăii, RO. The lowest HT performances were recorded for: 9 – Merritt, CA; 5 – El Dorado, USA and 52 – Shuswape Lake (Figure 4).

In the Făget comparative trial, the top HT performers were: 41 – Prüm Süd – Abt. 79 C, DE; 33 – Yacolt – Spotted Deernt – Battle G., USA; 34 – Vicinity, Mineral Walker Road, USA; 2 – Idaho (var. *glauca*), USA and 12 – Diablo Dam – Whatcom, USA. The lowest performances were: 17 – Kittitas – Cle Elum, USA; 13 – Skagit – Sedro Woolley, USA and 4 – Boise (var. *glauca*), USA (Figure 4).

In the Padeș comparative trial, the top HT provenances were: 46 – Les Farges III, FR; 44 – Manderscheid – Abt. 36 B2, DE; 59 – Toplița, RO; 17 – Kittitas – Cle Elum, USA and 67 – Kelso, USA. The lowest HT performances were recorded for: 9 – Merritt, CA; 29 – Vancouver, CA and 20 – Benton – Corvallis, USA (Figure 4).

In terms of mean HT at the trial level, the highest value was recorded at Aleșd (30.2 m), followed by Făget (29.6 m), while Padeș had the lowest (28.8 m).

4.1.3. Volumul mediu/arbore (VOL)

The mean VOL values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 5.

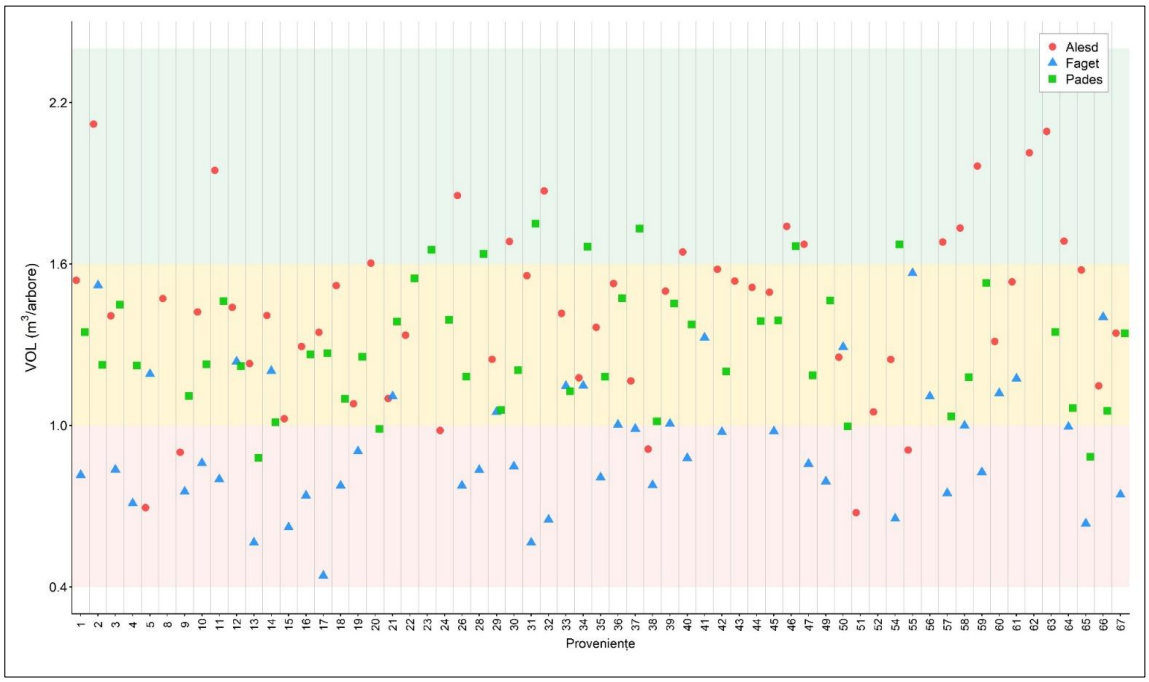

Fig. 5 Variation in mean tree volume of Douglas-fir provenances tested in the provenance trials

In the Aleșd, Făget, and Padeș provenance trials, the analysis of mean tree volume yields a ranking similar to that obtained from DBH (see Subchapter 4.1.1). Provenances with high DBH values also exhibit the highest volumes, while those with below-average DBH values show lower volumes.

In terms of mean VOL at the trial level, the highest value was recorded at Aleșd (1.43 m^3 $tree^{-1}$), followed by Padeș (1.29 m^3 $tree^{-1}$), while Făget ranked last with 0.93 m^3 $tree^{-1}$.

4.1.4. Basal area (SB)

The mean SB values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 6.

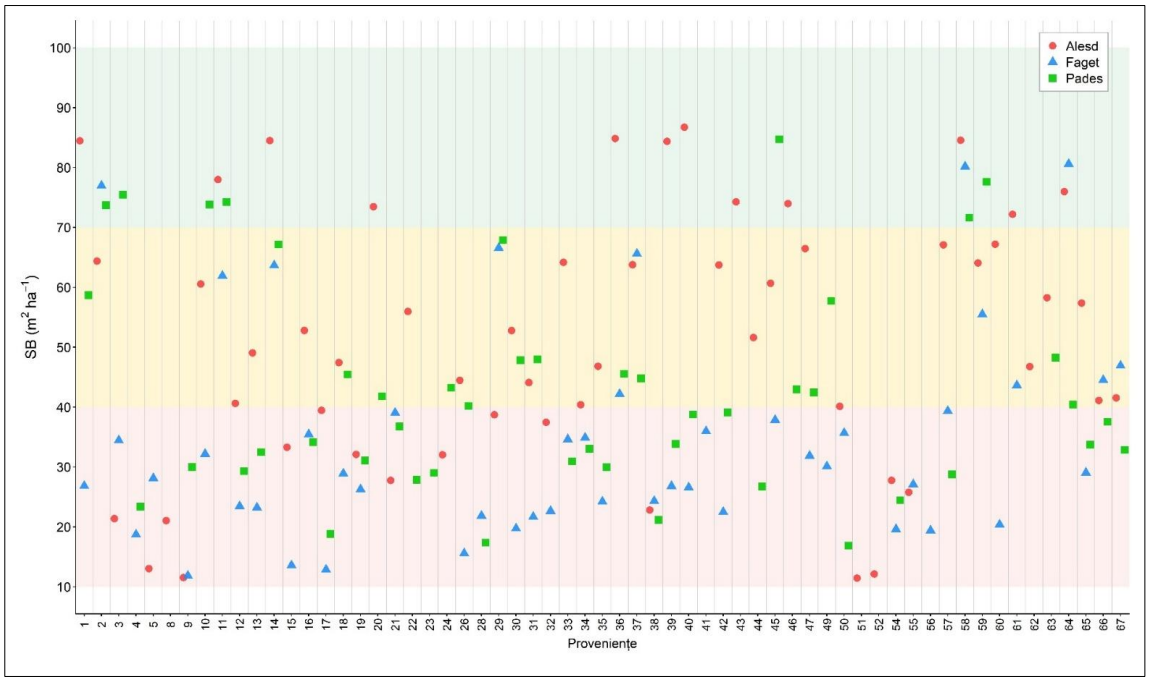

Fig. 6 Variation in basal area of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, based on SB performance, the top-ranked provenances were: 40 – Daun Ost – Abt. 46 C., DE; 36 – Skycomish – Beckler Peak, USA; 58 – Piatra Albă, RO; 14 – Snohomish – Sloan Creek, USA and 1 – Idaho (var. *glauca*). The lowest SB performances were recorded for: 51 – Pinetan, CA; 9 – Merritt, CA and 52 – Shuswape Lake, CA (Figure 6).

In the Făget comparative trial, the top SB performers were: 64 – Anina – Buhui, RO; 58 – Piatra Albă, RO; 2 – Idaho (var. *glauca*), USA; 29 – Vancouver, CA and 37 – Concrete – Presentin Creek, USA. The lowest performances were: 9 – Merritt, CA; 17 – Kittias – Cle Elum, USA and 15 – Jefferson – Hoh River, USA (Figure 6).

In the Padeș comparative trial, the top SB provenances were: 45 – Poinsat – Puy de Dôme, FR; 59 – Toplița, RO; 3 – Idaho (var. *glauca*), USA; 11 – Duncan, DE and 10 – Franklin River, CA. The lowest SB performances were recorded for: 50 – Clallam County – Louella, USA; 28 – Chatcolet, S. (var. *glauca*), USA and 17 – Kittitas – Cle Elum, USA (Figure 6).

In terms of mean SB at the trial level, the highest value was recorded at Aleșd (51.2 m² ha^{-1}), followed by Padeș (42.7 m² ha^{-1}), while Făget ranked last with 34.8 m² ha^{-1}.

4.1.5. Genotype × environment interaction for quantitative traits

The results of the analysis of variance highlight the influence of site (L), provenance (P), and the provenance × site interaction (P × L) on the analysed quantitative traits (Table 5).

Tab. 5 Genotype × environment interaction

Source of variation	DF	Variance (s^2)			
		DBH	HT	VOL	SB
Provenance (P)	37	43.450 ***	12.135 *	0.235 **	2379.8 ***
Locality (L)	2	2040.1 ***	78.70 ***	6.768 ***	8953.6 ***
Interaction (P × L)	74	49.691 ***	17.538 ***	0.235 ***	868.1 ***
Error	189	18.983	7.497	0.11	416.5

Notă: Significance levels: p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); DBH – diameter at 1.30 m; HT – total height; VOL – tree volume; SB – basal area.

Provenance (P) showed highly significant effects for DBH, VOL, and SB ($p < 0.001$), as well as a significant effect for HT ($p \leq 0.05$). The analysis of variance revealed highly significant effects of site (L) for all analysed traits: DBH, HT, VOL, and SB ($p < 0.001$). The provenance × site interaction (P × L) was highly significant for all quantitative traits analysed, namely DBH, HT, VOL, and SB ($p \leq 0.001$).

4.1.6. Discussion of quantitative traits

The results highlight significant genetic variability among Douglas-fir provenances; however, its intensity varies by test site and trait analysed (Table 4). In the Aleșd provenance trial, provenance has a highly significant effect for all traits, indicating clear genetic differentiation, whereas at Făget the effect is significant but with a reduced contribution to total variance, and at Padeș it is variable, being significant only for certain traits (Eilmann et al. 2013; Ye and Jayawickrama 2024; Montwé et al. 2015; Neophytou et al. 2016; Gričar et al. 2024; Bastien et al. 2013; Petkova et al. 2014; Popov 2014; Smolnikar et al. 2021).

The analysis of variance components shows that residual variance is dominant across all provenance trials, indicating the major influence of environmental factors on the analysed traits, whereas the genetic component, although significant, contributes less (Cappa et al. 2019; Robinson et al. 2007). The replication effect is not significant at Aleșd and Padeș, suggesting relatively homogeneous conditions, but is significant at Făget for some traits, indicating micro-site heterogeneity. Edaphic conditions and slope differences among sites contribute to variation in growth, with more favourable conditions at Aleșd and Padeș than at Făget.

Performance analysis highlights the presence of provenances with stable and superior performance across all trials, such as Idaho (USA), Skykomish (USA), Daun (Germany), Poinsat (France), and Toplița (Romania), as well as good performance of some local provenances, indicating good adaptation to Romanian conditions.

In terms of total height, a group of provenances from the USA, Germany, France, and Canada shows consistently high performance across all sites, and some provenances are stable for both DBH and HT, indicating ecological stability. The results confirm the general superiority of coastal provenances under European conditions, while interior provenances are better suited to continental conditions (van Loo et al. 2019; Milenkova et al. 2018; Neophytou et al. 2022).

The analysis of variance indicates that both provenance and site significantly influence the analysed traits, and the provenance × site interaction is highly significant, reflecting a differentiated response of provenances depending on environmental conditions (Dungey et al. 2012; Liao et al. 2023; Chakraborty et al. 2024; Benito Garzón et al. 2019).

Overall, the results highlight the combined role of genetic and environmental factors, as well as the importance of phenotypic plasticity in Douglas-fir adaptation, providing a solid basis for the selection of valuable provenances and for the development of genetic improvement programs in Romania.

4.2. Genetic variability of wood quality and adaptive traits

The results of the statistical analysis obtained using the linear model are summarised in Table 6, highlighting the effects of the sources of variation on the wood quality and adaptive traits analysed within each provenance trial.

Tab. 6 Results of the linear model for the wood quality and adaptive traits analysed in each provenance trial

Trial	Trait	LRTp	Vp	Vr	MS rep	Mean ± SD
			WOOD QUALITY TRAITS			
Aleșd	PH	24.55 ***	0.98 (12%)	7.34 (88%)	228.08*	17.3 ± 2.91
	SF	1.67 ^{ns}	0.01 (3%)	0.28 (97%)	0.01 ^{ns}	4.47 ± 0.53
	NB	6.68 **	0.04 (3%)	1.14 (97%)	3.15 ^{ns}	2.16 ± 1.09
	DB	14.53 **	0.04 (7%)	0.56 (93%)	1.71 ^{ns}	2.13 ± 0.77
	BA	26.18 **	0.03 (7%)	0.42 (93%)	0.45 ^{ns}	1.66 ± 0.68
	FI	2.81 ^{ns}	0.01 (3%)	0.31 (97%)	0.04 ^{ns}	3.66 ± 0.57
			ADAPTIVE TRAITS			

	SI	12.09 ***	0.06 (9%)	0.57 (91%)	0.25 ns	0.86 ± 0.15
	SV	35.56 ***	39.96 (48%)	42.77 (52%)	108.04 ns	18.47 ± 0.09
				WOOD QUALITY TRAITS		
Făget	PH	34.01 ***	1.73 (13%)	12.05 (87%)	735.91 ***	17.2 ± 3.86
	SF	0.54 ns	0.01 (2%)	0.45 (98%)	0.79 ns	4.59 ± 0.67
	NB	0.44 ns	0.01 (1%)	1.58 (99%)	2.07 ns	2.26 ± 1.26
	DB	12.34 ***	0.05 (7%)	0.63 (93%)	2.97 *	2.01 ± 0.82
	BA	15.38 ***	0.35 (44%)	0.44 (56%)	0.06 ns	1.84 ± 0.68
	FI	4.60 ns	0	0.90 (100%)	0.01 ns	3.96 ± 0.30
				ADAPTIVE TRAITS		
	SI	6.86 **	0.001 (3%)	0.34 (97%)	0.57 ns	1.06 ± 0.19
	SV	0 ns	0	92.14 (100%)	254.74 ns	16.85 ± 9.65
				WOOD QUALITY TRAITS		
Padeș	PH	7.78 **	0.38 (5%)	6.74 (95%)	20.02 ns	17.7 ± 2.67
	SF	0.34 ns	0.002 (1%)	0.27 (99%)	0.33 ns	4.66 ± 0.53
	NB	0.99 ns	0.02 (1%)	1.46 (99%)	0.08 ns	2.26 ± 1.22
	DB	2.50 ns	0.01 (2%)	0.57 (98%)	2.96 *	2.04 ± 0.77
	BA	8.60 **	0.03 (6%)	0.48 (94%)	0.12 ns	1.95 ± 0.71
	FI	0.23 ns	0	0.11 (100%)	0.01 ns	3.89 ± 0.34
				ADAPTIVE TRAITS		
	SI	2.07 ns	0	0.22 (100%)	0.22 ns	0.85 ± 0.15
	SV	0.01 ns	0.55 (1%)	63.40 (99%)	26.04	16.60 ± 8.06

Note: *Significance levels: p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); ns – not significant (p > 0.05); LRTp – likelihood ratio test for the provenance effect; Vp – variance of the random provenance effect; Vr – residual variance; MS rep – mean square for replication; PH – pruned height; SF – stem form; NB – number of branches; DB – branch diameter; BA – branch insertion angle; FI – forking; SI – slenderness index; SV – survival.*

In the Aleșd provenance trial, the effect of provenance on wood quality traits was highly significant for PH and significant for NB, DB, and BA, but not for SF and FI. For adaptive traits, the provenance effect was highly significant for SV and SI. Provenance variance accounted for 3–12% of the variance in wood quality traits and 9–48% in adaptive traits, with the remainder explained by residual variance. The replication effect was not significant, except for PH (Table 6).

In the Făget provenance trial, the provenance effect was highly significant for PH, DB, and BA, but not significant for SF, NB, and FI. For adaptive traits, the provenance effect was significant only for SI, not for SV. Provenance variance ranged between 3–13% for most traits, with higher values for BA, and the replication effect was significant for PH and DB (Table 6).

In the Padeș provenance trial, the provenance effect was significant only for PH and BA, being non-significant for the other wood quality and adaptive traits. Provenance variance was low, below 6%, and the replication effect was significant only for DB (Table 6).

4.2.1. Genetic variability of wood quality traits

4.2.1.1 Pruned height (PH)

The mean PH values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 7.

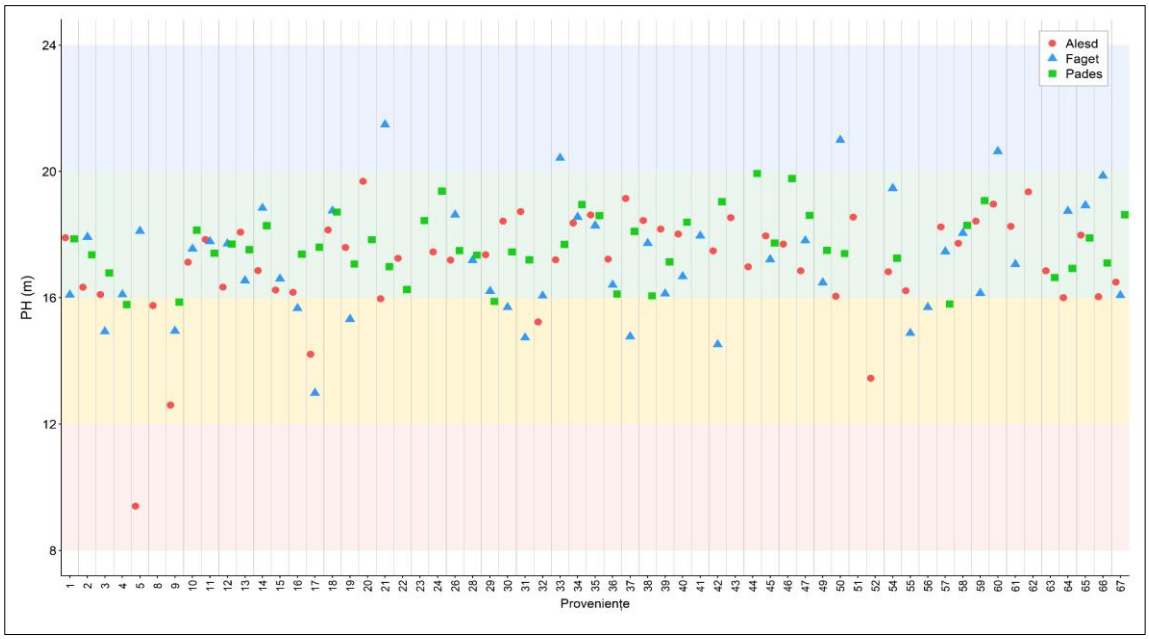

Fig. 7 Variation in pruning height of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, based on PH performance, the top-ranked provenances were: 5 – El Dorado, USA; 9 – Merritt, CA; 52 – Shuswape Lake, CA; 17 – Kittias – Cle Elum, USA and 32 – Pe Ell – Sand Creek, Mc. Donald, USA. The lowest PH performances were recorded for: 31 – Elma, USA; 60 – Aninoasa Mare, RO and 37 – Concrete – Presentin Creek, USA (Figure 7).

In the Făget comparative trial, the top PH performers were: 17 – Kittias – Cle Elum, USA; 42 – Wittlich West – Abt. 3B, DE; 31 – Elma, USA; 37 – Concrete – Presentin Creek, USA and 55 – Centre Creek – Chilliwack Valley, CA. The lowest performances were: 66 – Elbe, USA; 33 – Yacolt – Spotted Deernt – Battle G., USA and 60 – Aninoasa Mare, RO (Figure 7).

In the Padeș comparative trial, the top PH provenances were: 4 – Boise (var. *glauca*), USA; 57 – Pădurea Neagră, RO; 9 – Merrit, CA; 29 – Vancouver, CA and 38 – Oyster R., CA. The lowest PH performances were recorded for: 42 – Wittlich West – Abt. 3B, DE; 59 – Toplița, RO and 24 – Jackson – Ashland, USA (Figure 7).

In terms of mean PH at the trial level, values were relatively similar, with 17.3 m at Aleșd, 17.2 m at Făget, and 17.7 m at Padeș.

4.2.1.2 Branch insertion angle (BA)

The mean BA values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 8.

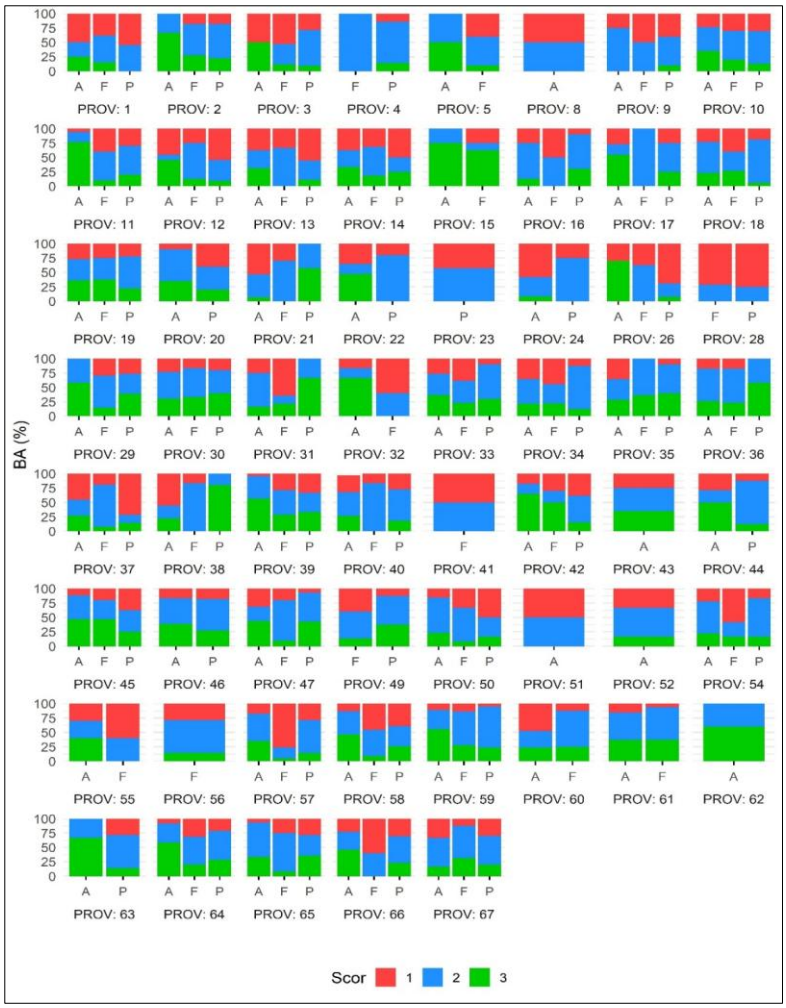

Fig. 8 Variation in branch insertion angle of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, in the superior performance class (score 3, angle > 90°), the following provenances were identified: 16 – Grays Harbour – Humptulips, USA; 33 – Yacolt – Spotted Deernt – Battle G., USA; 3 – Idaho (var. *glauca*), USA; 5 – El Dorado, USA and 9 – Merritt, CA (Figure 8).

In the Făget comparative trial, in the superior performance class (score 3, angle > 90°), the following provenances were identified: 15 – Jefferson – Hoh River, USA; 35 – Darrington – Texas Pond, USA; 61 – Vârful Dării, RO; 45 – Poinsat – Puy de Dome, FR and 42 – Wittlich West – Abt. 3B., DE (Figure 8).

In the Padeș comparative trial, in the superior performance class (score 3, angle > 90°), the following provenances were identified: 38 – Oyster R., CA; 31 – Elma, USA; 36 – Skycomish – Beckler Peak, USA; 21 – Marion Forks, USA and 47 – Moussans II, FR (Figure 8).

4.2.1.3. Branch diameter (DB)

The mean DB values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 9.

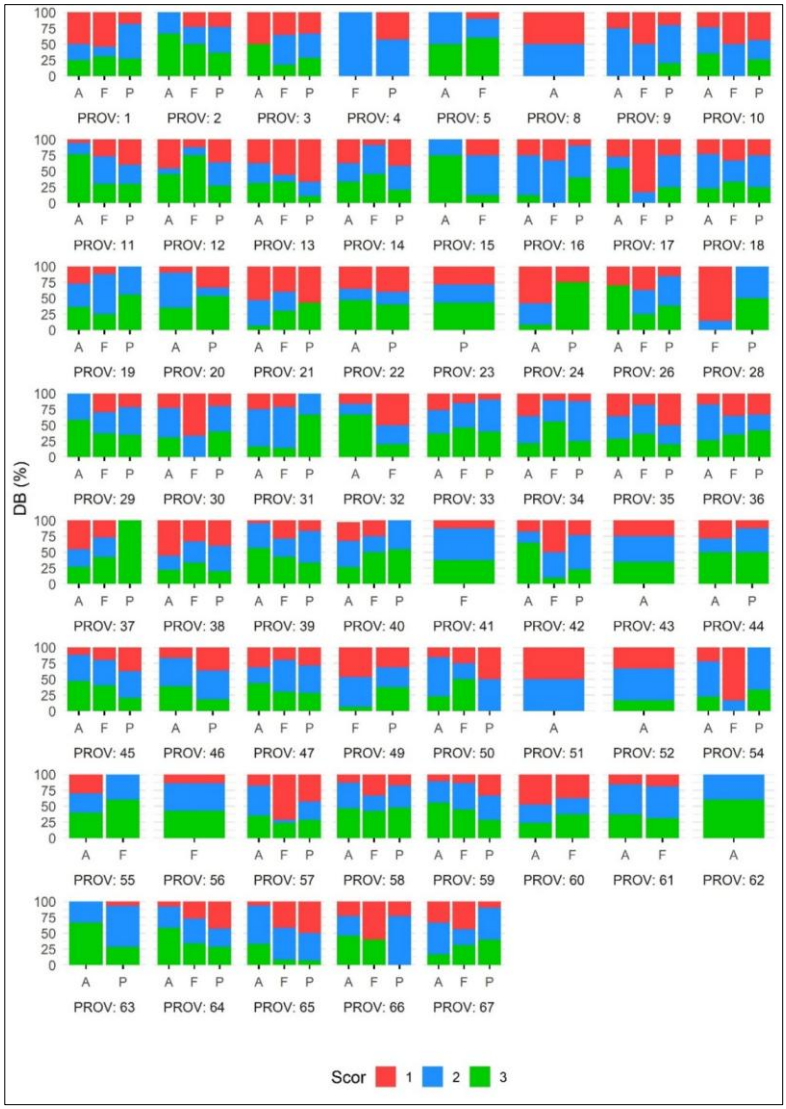

Fig. 9 Variation in branch diameter of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, based on DB performance, the top-ranked provenances for score 1 (DB < 2 cm) were: 8 – South End Pass, USA; 24 – Jakson – Ashland, USA; 51 – Pinetan, CA; 21 – Marion Forks, USA and 38 – Oyster R., CA. Provenances with score 3 (DB > 5 cm) were: 62 – Vârful Dăii, RO; 2 – Idaho (var. *glauca*), USA and 63 – Nădrăgel, RO (Figure 9).

In the Făget comparative trial, for score 1 (DB < 2 cm), the top provenances were: 28 – Chatcolet, S. (var. *glauca*), USA; 17 – Kittias – Cle Elum, USA; 54 – Morton Lake, CA; 30 – Hoodsport, USA and 9 – Merrit, CA. Provenances with score 3 (DB > 5 cm) were: 34 – Vicinity, Mineral Walker Road, USA; 5 – El Dorado, USA and 33 – Yacolt – Spotted Deernt – Battle G., USA (Figure 9).

In the Padeș comparative trial, for score 1 (DB < 2 cm), the top provenances were: 13 – Skagit – Sedro Wooley, USA; 50 – Clallam Country – Louella, USA and 4 – Boise (var. *glauca*), USA; 65 – Sedro Wooley, USA and 35 – Darrington – Texas Pond, USA. Provenances with score 3 (DB > 5 cm) were: 28 – Chatcolet, S. (var. *glauca*), USA; 40 – Daun Ost – Abt. 46 C., DE and 19 – Pine Grove, USA (Figure 9).

4.2.1.4 Number of branches (NB)

The mean NB values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 10.

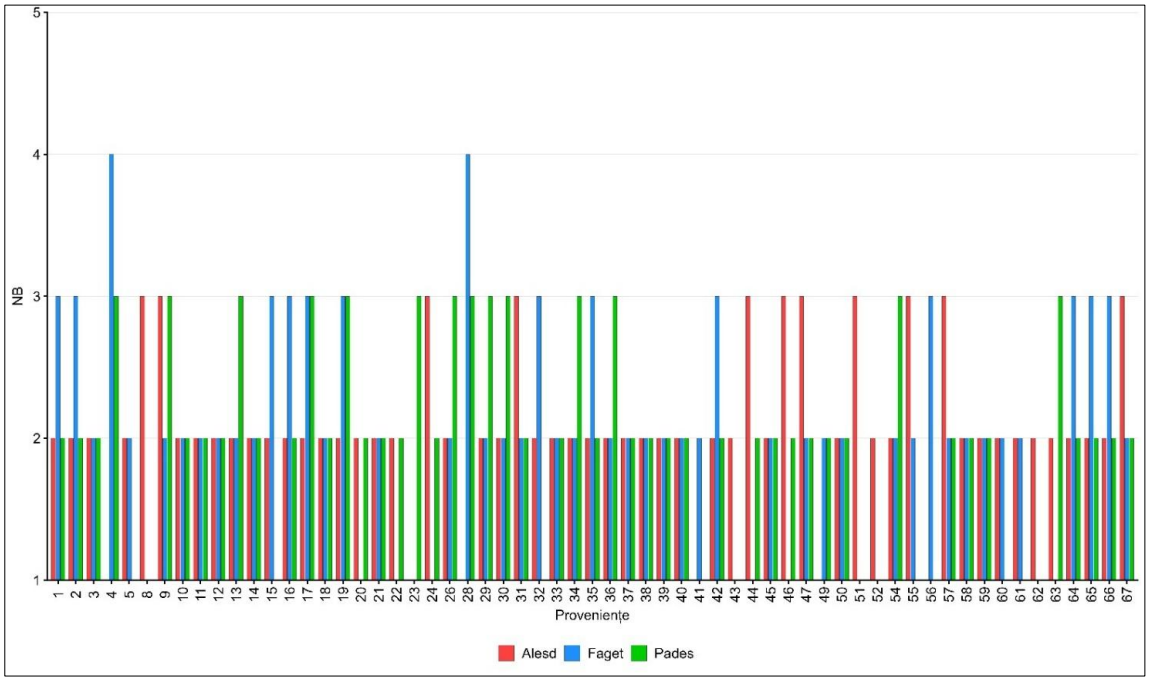

Fig. 10 Variation in the number of branches of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, the lowest mean NB values were recorded for the following provenances: 1 – Idaho (var. *glauca*), USA; 3 – Idaho (var. *glauca*), USA; 5 – El Dorado, USA; 58 – Piatra Albă, RO and 62 – Vârful Dăii, RO. The highest mean NB values were recorded for: 46 – Les Farges III, FR; 8 – South End Pass, USA and 9 – Merritt, USA (Figure 10).

In the Făget comparative trial, the lowest mean NB values were recorded for: 9 – Merritt, CA; 47 – Moussans II, FR; 39 – Daun Ost – Abt. 39 A., DE; 34 – Vicinity, Mineral Walker Road, USA and 59 – Toplița, RO. The highest mean NB values were recorded for: 17 – Kittias – Cle Elum, USA; 32 – Pe Ell – Sand Creek, Mc. Donald, USA and 66 – Elbe, USA (Figure 10).

In the Padeș comparative trial, the lowest mean NB values were recorded for: 24 – Jackson – Ashland, USA; 39 – Daun Ost – Abt. 39 A., DE; 33 – Yacolt – Spotted Deernt – Battle G., USA; 66 – Elbe, USA and 1 – Idaho (var. *glauca*), USA. The highest mean NB values were recorded for: 30 – Hoodsport, USA; 54 – Shuswape Lake, CA and 13 – Skagit – Sedro Wooley, USA (Figure 10).

4.3. Genetic variability of adaptive traits

4.3.1. Survival (SV)

The mean SV values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 11.

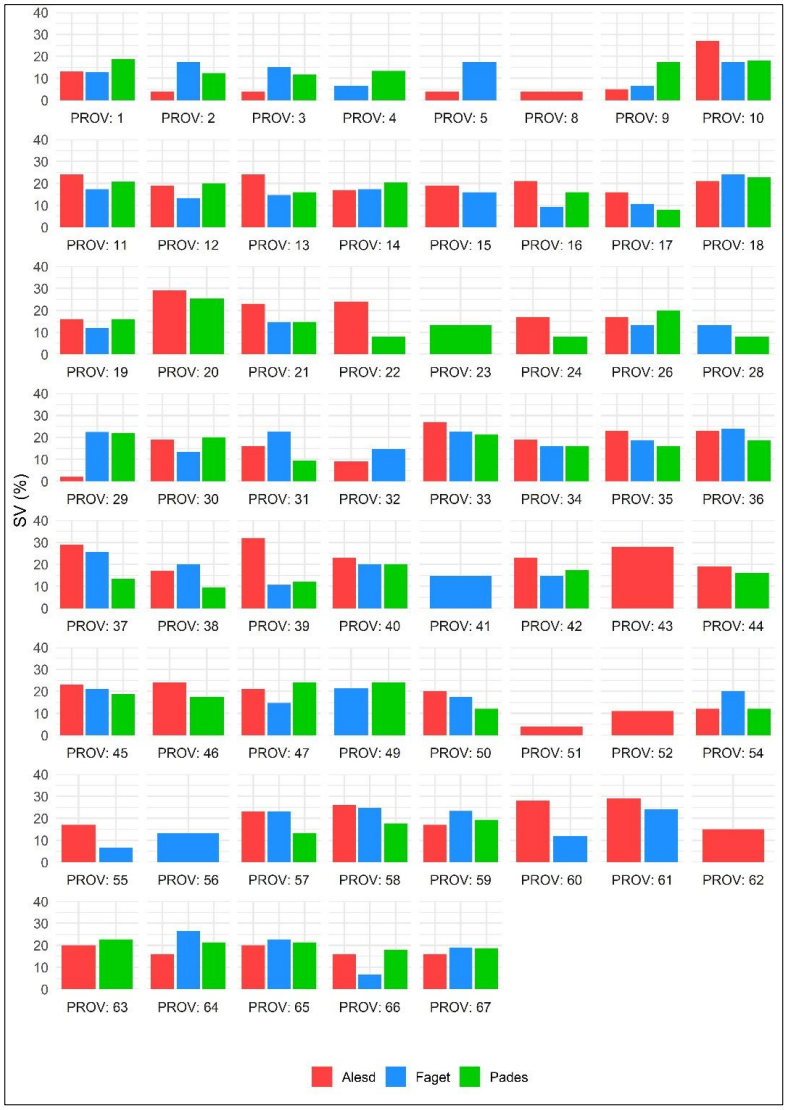

Fig. 11 Variation in survival of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, the highest SV percentages were recorded for the following provenances: 39 – Daun Ost – Abt. 39 A., DE; 61 – Vârful Dăii, RO; 37 – Concrete – Presentin Creek, USA; 20 – Benton – Corvallis, USA and 60 – Aninoasa Mare, RO. The lowest SV percentages were recorded for: 8 – South End Pass, USA; 5 – El Dorado, USA and 3 – Idaho (var. *glauca*), USA (Figure 11).

In the Făget comparative trial, the highest SV percentages were recorded for: 64 – Anina – Buhui, RO; 37 – Concrete – Presentin Creek, USA; 58 – Piatra Albă, RO; 18 – Lewis – Packwood, USA and 36 – Skycomish – Beckler Peak, USA. The lowest SV percentages were recorded for: 16 – Grays Harbour – Humptulips, USA; 4 – Boise (var. *glauca*), USA and 9 – Merritt, CA (Figure 11).

In the Padeș comparative trial, the highest SV percentages were recorded for: 20 – Benton – Corvallis, USA; 47 – Moussans II, FR; 49 – Darrington III, USA; 18 – Lewis – Packwood, USA and 63 – Nădrăgel, RO. The lowest SV percentages were recorded for: 38 – Oyster R., CA; 17 – Kittias – Cle Elum, USA and 22 – Lane – Oakridge, USA (Figure 11).

In terms of mean SV at the trial level, the highest value was recorded at Aleșd (18.47%), followed by Făget (16.85%), while Padeș ranked last with 16.60%.

4.3.2. Slenderness index (SI)

The mean SI values of the analysed Douglas-fir provenances across the three provenance trials are presented in Figure 12.

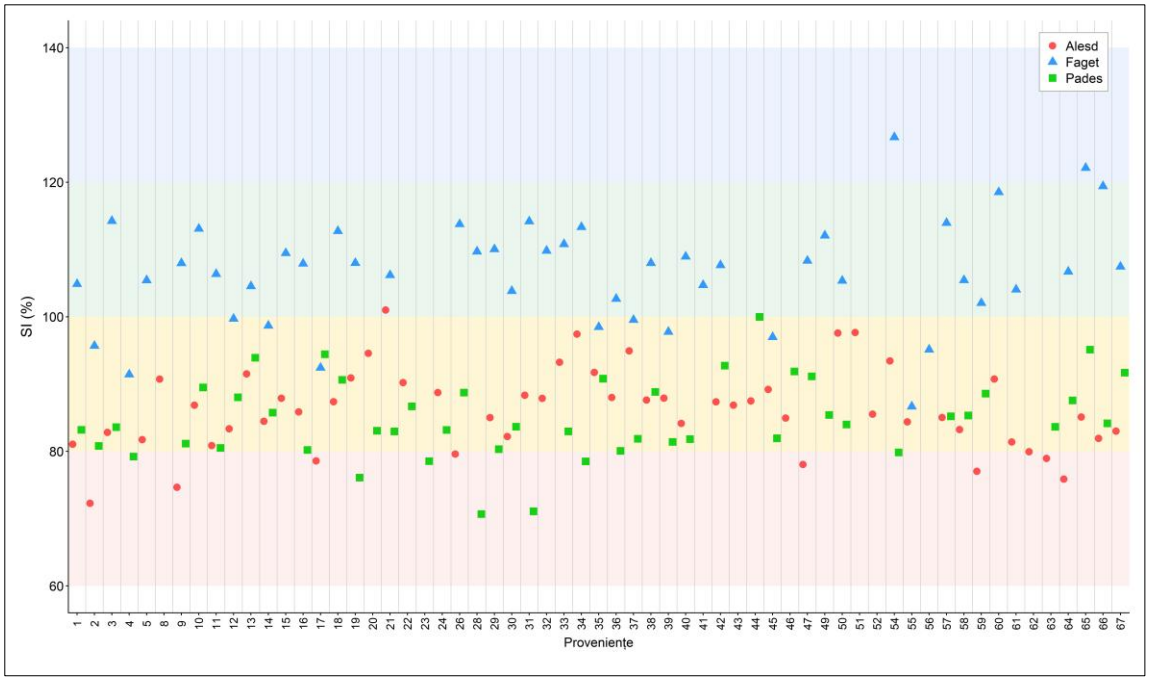

Fig. 12 Variation in slenderness index of Douglas-fir provenances tested in the provenance trials

In the Aleșd comparative trial, regarding SI (where lower values indicate higher stability), the top-ranked provenances were: 2 – Idaho (var. *glauca*), USA; 9 – Merrit, CA; 64 – Anina – Buhui, RO; 59 – Toplița, RO and 47 – Moussans II, FR. Provenances with higher SI values (indicating greater

vulnerability) were: 37 – Concrete – Presentin Creek, USA; 34 – Vicinity, Mineral Walker Road, USA and 50 – Clallam County – Louella, USA (Figure 12).

In the Făget comparative trial, regarding SI (where lower values indicate higher stability), the top-ranked provenances were: 55 – Centre Creek – Chilliwack Valley, CA; 4 – Boise (var. *glauca*), USA; 17 – Kittias – Cle Elum, USA; 56 – Devine – Dist., DE and 2 – Idaho (var*. glauca*), USA. Provenances with higher SI values (indicating greater vulnerability) were: 3 – Idaho (var. *glauca*), USA; 60 – Aninoasa Mare, RO and 66 – Elbe, USA (Figure 12).

In the Padeș comparative trial, regarding SI (where lower values indicate higher stability), the top-ranked provenances were: 28 – Chatcolet, S. (var. *glauca*), USA; 31 – Elma, Washington; 19 – Pine Grove, USA; 34 – Vicinity, Mineral Walker Road, USA and 23 – Rosenburg, USA. Provenances with higher SI values (indicating greater vulnerability) were: 42 – Wittlich West – Abt. 3B; 13 – Skagit – Sedro Wooley, USA and 17 – Kittias – Cle Elum, USA (Figure 12).

In terms of mean SI at the trial level, the lowest value was recorded at Padeș (85%), followed by Aleșd (86%), while Făget showed the highest value (107%).

4.3.3. Genotype × environment interaction for wood quality and adaptive traits

The results of the analysis of variance highlight the effect of site (L), provenance (P), and the provenance × site interaction (P × L) on wood quality and adaptive traits (Table 7).

Tab. 7 Genotype × environment interaction

Source of variation	DF	Variance (s^2)							
		PH	SF	NB	DB	BA	FI	SI	SV
Provenance (P)	37	9.896 ***	0.162 ns	0.516 ns	0.361 **	1.685 **	1.224 ns	0.009 ns	124.70 ***
Locality (L)	2	8.267 ns	0.804 **	0.981 ns	1.073 **	1.294 **	1.098 ***	1.388 ***	431.23 ***
Interaction P × L	74	5.393 ns	0.171 ns	0.666 ns	0.326 *	0.236 ns	0.074 ns	0.11 *	61.629 ns
Error	188	4.184	0.095	0.453	0.190	0.195	0.084	0.008	48.611

Note: *Significance levels: p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); ns – not significant (p > 0.05); PH – pruned height; SF – stem form; NB – number of branches; DB – branch diameter; BA – branch insertion angle; FI – forking; SI – slenderness index; SV – survival.*

Provenance (P) showed a highly significant effect for SV and PH ($p \leq 0.001$), and a significant effect for DB and BA ($p \leq 0.01$), while for SF, NB, BA, FI, and SI, the provenance effect was not significant ($p > 0.05$). The analysis of variance revealed highly significant effects of site (L) for FI, SI, and SV ($p \leq 0.001$), and significant effects for SF, DB, and BA ($p \leq 0.01$). For PH, NB, and DB, the site effect was not significant ($p > 0.05$). The provenance × site interaction (P × L) was significant for DB and SI, while for PH, SF, NB, BA, FI, and SV it was not significant ($p > 0.05$).

4.3.4. Discussion of wood quality and adaptive traits

The results highlight differentiated responses among Douglas-fir provenances across test sites, confirming the important role of site conditions in the expression of wood quality and adaptive traits. Overall, the variation attributable to provenance was low to moderate, and the significance of the genetic effect varied by test site and trait.

In the Aleșd provenance trial, provenance had a significant effect on several wood quality traits (PH, NB, DB, BA) and adaptive traits (SV, SI), indicating a genetic contribution to phenotypic variation, particularly for survival. At Făget, provenance significantly influenced PH, DB, BA, and SI, while SV was predominantly determined by environmental factors. In the Padeș provenance trial, the effect of provenance was limited, being significant only for PH and BA, with most traits dominated by residual variation.

Differences among sites reflect the influence of site conditions, with Aleșd favouring the expression of genetic variation, while at Făget and Padeș, environmental factors played a more pronounced role. Overall, the site effect was dominant for most traits, especially for SV, SI, and FI, confirming the strong influence of the environment on phenotypic expression (Li et al. 2017; Magalska and Howe 2014). The provenance × site interaction was significant only for DB and SI, indicating differences in provenance responses across sites for these traits (Campbell 1992; Chauvin et al. 2019).

Branch-related traits (NB, DB, BA) play a key role in wood quality, influencing knot size and mechanical properties, as highlighted in numerous studies (Osborne and Maguire 2016; Lowell et al. 2014; Macdonald and Hubert 2002; Longo et al. 2019; Todoroki et al. 2005).

Overall, the results confirm the existence of significant genetic variability, but one that is strongly influenced by environmental conditions (Di Fabio et al. 2024; Hankin et al. 2023; Kerns et al. 2020; Pedlar et al. 2024).

4.4. Selection of the best provenances using selection indices

To include multiple traits and avoid the limitations of univariate selection, multivariate selection based on selection indices was applied in this study. This approach allows the selection of provenances that combine superior performance with greater stability, thus supporting decision-making for future use of Douglas-fir.

4.4.1. Selection of provenances within each provenance trial using the MGIDI index

The application of the MGIDI index allowed the identification of a group of provenances with superior performance in each provenance trial. The selection intensity was maintained at 20%, resulting in the selection of 11 provenances out of 55 tested at Aleșd, 10 out of 49 at Făget, and 10 out of 48 at Padeș. All selected provenances recorded values above the trial means for DBH, HT, and SV (Table 8).

Tab. 8 Differences obtained through selection using the MGIDI index for the tested Douglas-fir provenances

Trait	Trial mean			Mean of selected provenances			Difference %		
	Aleșd	Făget	Padeș	Aleșd	Făget	Padeș	Aleșd	Făget	Padeș
DBH	35.9	28.8	34.7	39.9	31.2	35.4	11.1	8.3	2
HT	30.2	29.6	28.8	32	31.8,9	28.8	6	7.4	0
SV	18.5	179	16.6	23.7	20.6	18.2	28.1	15.1	9.6

Notă: *DBH – diameter at 1.30 m; HT – total height; SV – survival.*

In the Aleșd provenance trial, the application of the MGIDI index resulted in the selection of provenances from five countries: Canada (1), USA (2), Germany (2), France (1), and Romania (5). From Canada, the Duncan provenance (British Columbia) was selected; from the USA, the provenances Benton–Corvallis (Oregon) and Siskiyou–Hawkinsville (California); from Germany, the provenances Daun Ost and Wittlich West; and from France, the provenance Les Farges III. The selected Romanian provenances were Piatra Albă, Toplița, Vârful Dăii, and Nădrăgel (Figure 18).

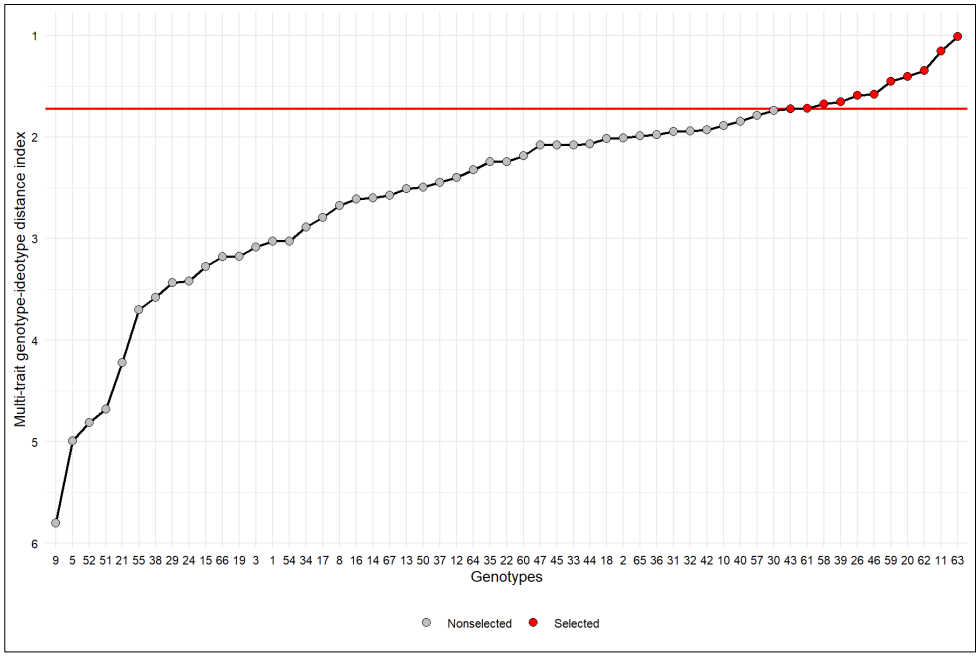

Fig. 13 Douglas-fir provenances selected based on the MGIDI index in the Aleșd provenance trial

In the Făget provenance trial, the application of the MGIDI index resulted in the selection of provenances from three countries: the USA (6), Germany (1), and Romania (3). The selected provenances from the USA were Idaho (var. *glauca*), El Dorado (California), Snohomish–Sloan Creek, Yacolt–Spotted Deer Mountain–Battle Ground, Skykomish–Beckler Peak, and Clallam County–Louella (Washington). From Germany, the provenance Prüm Süd was selected, and from Romania, the provenances Piatra Albă, Vârful Dăii, and Anina–Buhui (Figure 13).

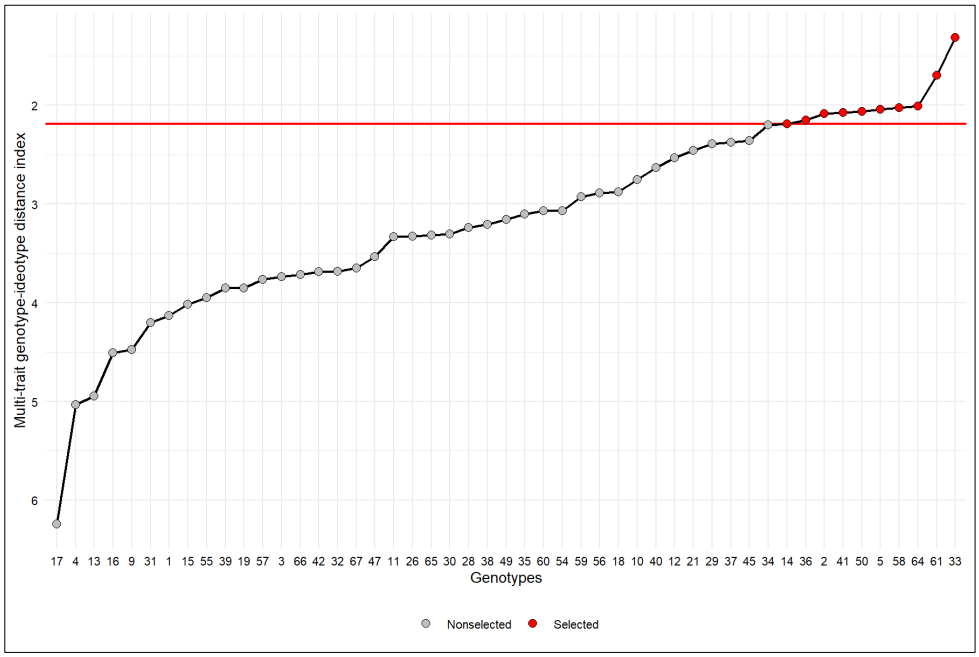

Fig. 14 Douglas-fir provenances selected based on the MGIDI index in the Făget provenance trial

In the Padeș provenance trial, the application of the MGIDI index resulted in the selection of provenances from four countries: USA (5), Germany (1), France (1), and Romania (1). The selected provenances from the USA were Pine Grove, Idaho (var. *glauca*); Boise, Idaho (var. glauca); and Hoodsport, Washington. From Germany, the provenance Darrington III was selected; from France, the provenance Poinsat–Puy de Dôme; and from Romania, the provenance Nădrăgel (Figure 14).

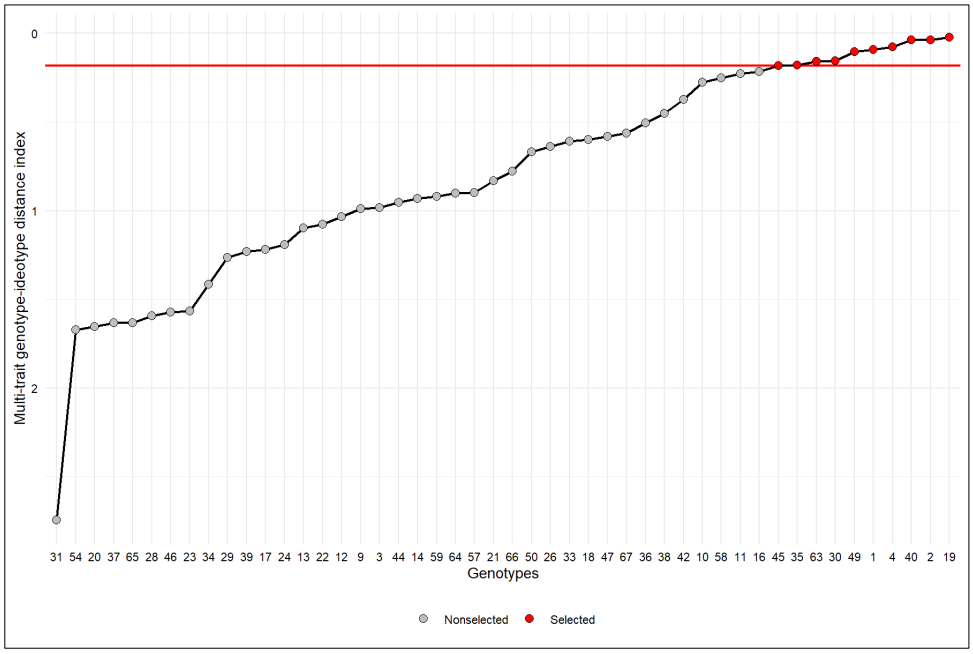

Fig. 15 Douglas-fir provenances selected based on the MGIDI index in the Padeș provenance trial

4.4.2. Selection of provenances based on the MTSI index across provenance trials

Based on the performance and stability of DBH, HT, and SV in the MTSI index, eight provenances that performed consistently across the three provenance trials were selected (Table 9). These originate from the USA (3), Canada (1), Romania (1), France (2), and Germany (1).

The selected provenances are: Skykomish–Beckler Peak, Concrete–Presentin Creek, and Hoodsport (USA); Franklin River (Canada); Piatra Albă (Romania); Poinsat–Puy de Dôme and Moussans II (France); and Daun Ost (Germany).

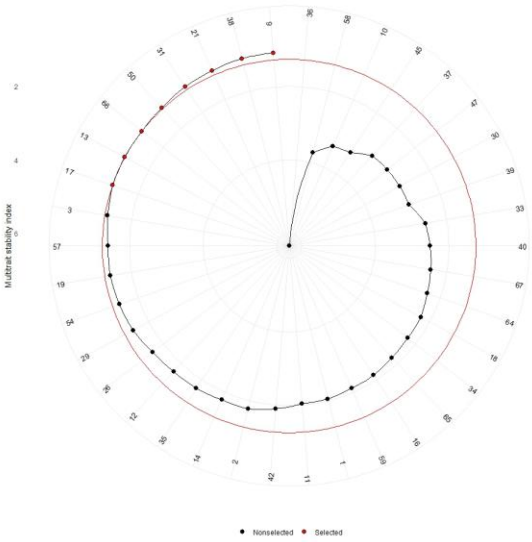

Fig. 16 Douglas-fir provenances selected based on the MTSI index across the three provenance trials

Tab. 9 Differences obtained through selection using the MTSI index for the tested Douglas-fir provenances

Trait	Trial mean			Mean of selected provenances			Difference %		
	Aleșd	Făget	Padeș	Aleșd	Făget	Padeș	Aleșd	Făget	Padeș
DBH	35,9	28,8	34.7	37.1	30.1	36.1	3.2	4.6	4
HT	30,2	29,6	28.8	30.9	30.1	29.3	2.4	1.7	2.6
SV	185	17.9	16.6	25.3	21.9	20	35	22.3	20.2

Notă: *DBH – diameter at 1.30 m; HT – total height; SV – survival.*

4.4.3. Discussion on multivariate selection using MGIDI and MTSI indices

The results highlight the high adaptive potential of Douglas-fir in Romania and the relevance of multivariate selection for breeding programs. The selected provenances exceeded the experimental means for all analysed traits, confirming the effectiveness of using selection indices. The application of the MGIDI index enabled the identification of high-performing provenances in each provenance trial, while maintaining genetic diversity through a selection intensity of 20% (Table 8).

Genetic gains were evident across all traits, with the highest values recorded for survival, particularly at Aleșd and Făget, consistent with studies on Douglas-fir variability and adaptability (Alexandru et al. 2023; Liepe et al. 2024; Li et al. 2017). For DBH and HT, gains were moderate but relevant for breeding programs, confirming their role in increasing productivity and economic value (Isaac-Renton et al. 2025).

The selected provenances varied among sites, reflecting the influence of site conditions on performance. At Aleșd, selection included provenances from multiple geographic regions, indicating high genetic potential under favourable conditions (Peláez et al. 2024), whereas at Făget and Padeș, selection was more restricted, highlighting a stronger influence of environmental factors. The presence of Romanian provenances among the selected groups confirms their adaptation to local conditions.

The application of the MTSI index enabled the identification of stable provenances across all provenance trials by combining the performance and stability of the analysed traits (Table 9). Genetic gains obtained through this approach were higher for survival, confirming the efficiency of selection for adaptive traits. These results are consistent with international studies highlighting the superiority of coastal provenances under various ecological conditions (Low et al. 2012; Malmqvist et al. 2018).

The selected provenances, due to their diverse ecological origins and demonstrated adaptability, can significantly contribute to promoting more resilient and better-adapted provenances in the context of climate change. These results are relevant for the development of future breeding strategies and for the forest management of Douglas-fir in western and south-western Romania.

4.5. Phenotypic correlations among the main analysed traits

The analysis of phenotypic correlations among the main traits highlights the degree of association among traits at the phenotypic level, resulting from the combined action of genetic and environmental factors. The results indicate differentiated relationships among traits, ranging from weak to strong correlations, both positive and negative. Phenotypic correlations were analysed separately for each provenance trial.

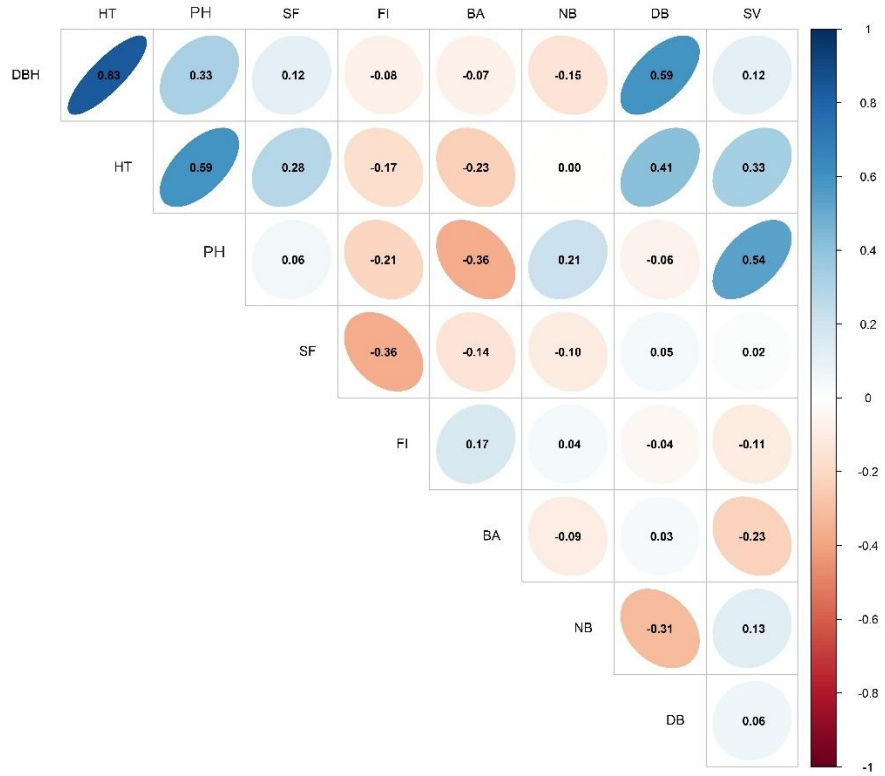

Fig. 17 Pearson correlations among the analysed traits in the Aleșd provenance trial

In the Aleșd provenance trial, positive correlations were observed between DBH – HT (r = 0.83), DBH – DB (r = 0.59), HT – PH (r = 0.59), HT – DB (r = 0.41), DBH – PH (r = 0.33), HT – SV (r = 0.33), and PH – SV (r = 0.54). Negative correlations were observed between PH – BA (r = –0.36), SF – FI (r = –0.36), BA – SV (r = –0.23), and HT – FI (r = –0.23). The other pairs of traits showed weak correlations, with Pearson coefficient values close to zero, indicating weak relationships between them.

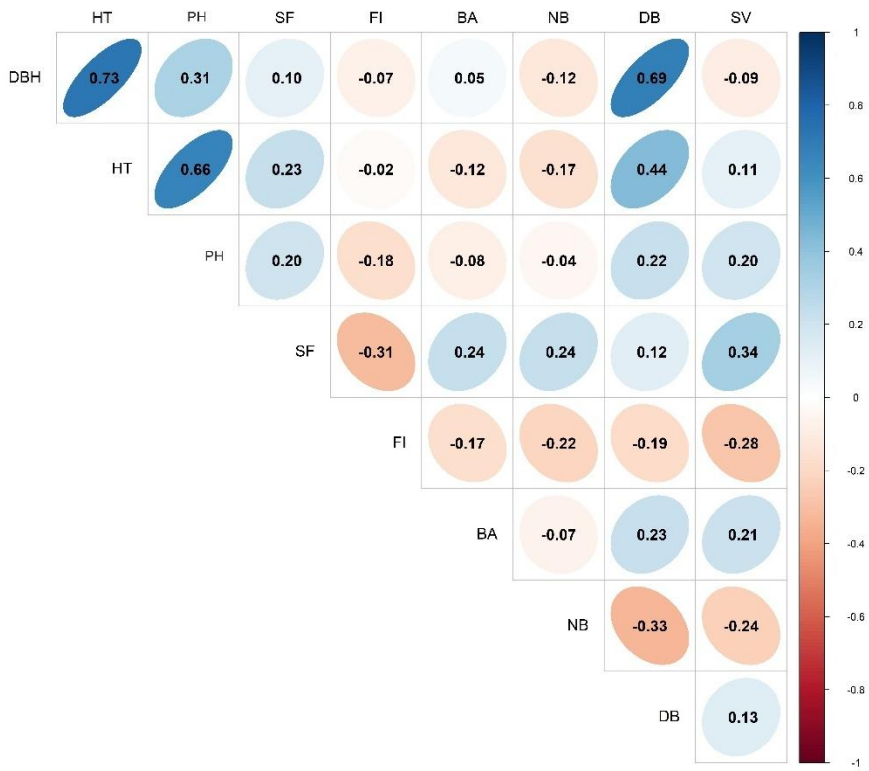

Fig. 18 Pearson correlations among the analysed traits in the Făget provenance trial

In the Făget provenance trial, positive correlations were observed between DBH – HT (r = 0.73), DBH – PH (r = 0.31), DBH – DB (r = 0.69), HT – PH (r = 0.66), HT – DB (r = 0.44), and SF – SV (r = 0.34). Negative correlations were observed between SF – FI (r = –0.31), FI – SV (r = –0.28), NB – DB (r = –0.33), and NB – SV (r = –0.24). The other pairs of traits showed weak correlations, with Pearson coefficient values close to zero, indicating weak relationships between them.

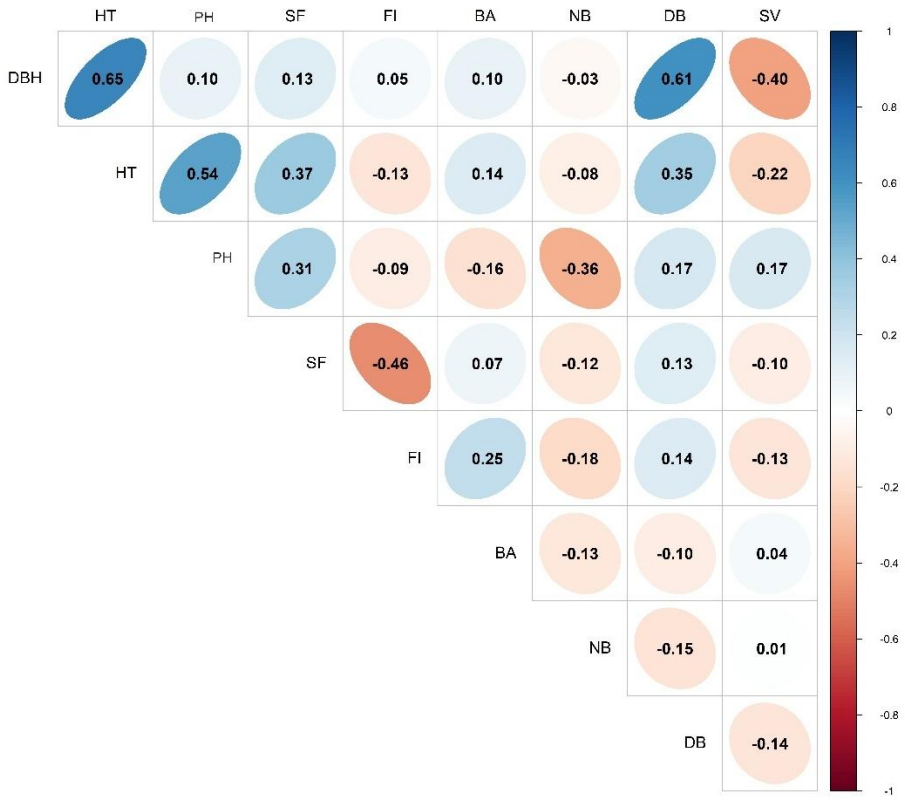

Fig. 19 Pearson correlations among the analysed traits in the Padeș provenance trial

In the Padeș provenance trial, positive correlations were observed between DBH – HT (r = 0.65), DBH – DB (r = 0.61), HT – PH (r = 0.54), HT – SF (r = 0.37), HT – DB (r = 0.35), PH – SF (r = 0.31), and FI – BA (r = 0.25). Negative correlations were observed between DBH–SV (r = –0.40), PH–NB (r = –0.36), and SF–FI (r = –0.46). The other pairs of traits showed weak correlations, with Pearson coefficient values close to zero, indicating weak relationships between them.

4.6. Correlations between the main analysed traits and the geographic gradients of provenance origin

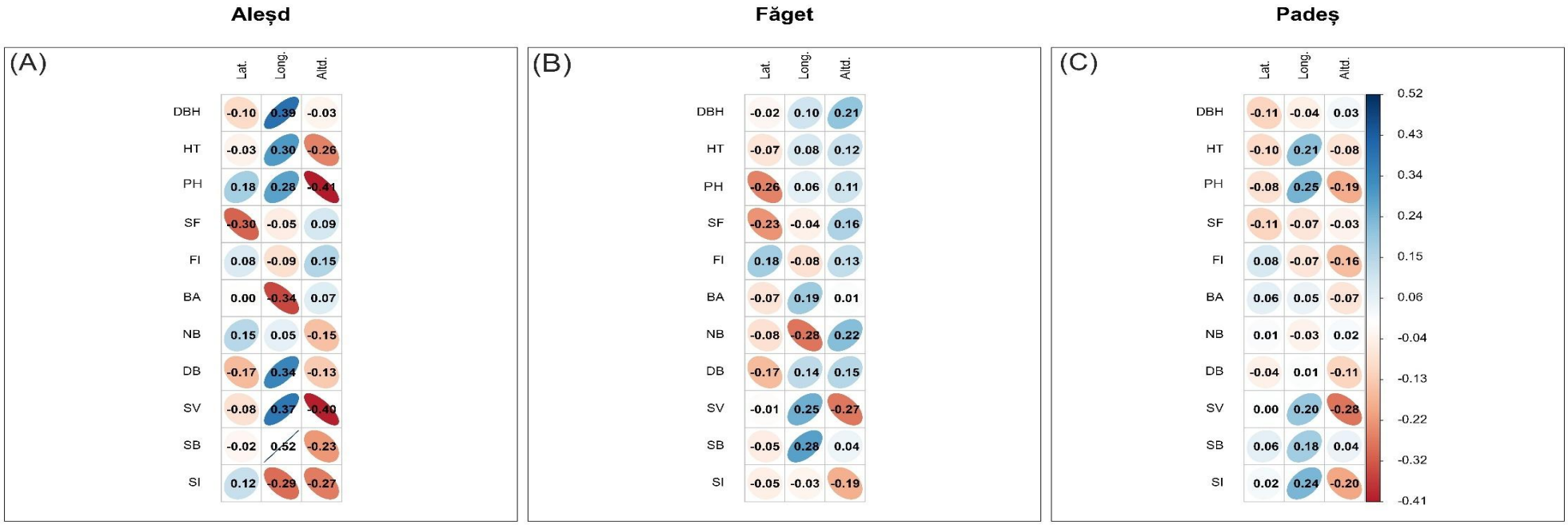

Fig. 20 Pearson correlations between the main analysed traits and the geographic gradients of provenance origin (latitude, longitude, and altitude) in each provenance trial (Aleșd – panel A, Făget – panel B, and Padeș – panel C).

In the Aleșd provenance trial, correlations with geographic gradients were observed for several analysed traits. With respect to latitude, negative correlations were found for SF (r = –0.30) and DB (r = –0.17), while positive correlations were observed for PH (r = 0.18), NB (r = 0.15), and SI (r = 0.12). With respect to longitude, positive correlations were identified for DBH (r = 0.39), HT (r = 0.30), PH (r = 0.28), DB (r = 0.34), SV (r = 0.37), and SB (r = 0.52), while BA (r = –0.34) showed a negative correlation and SI (r = 0.29) a positive one. With respect to altitude, negative correlations were identified for PH (r = –0.41), SV (r = –0.40), HT (r = –0.26), SI (r = –0.27), and SB (r = –0.23) (Figure 20 – panel A).

In the Făget provenance trial, correlations between the analysed traits and geographic gradients were generally of low to moderate intensity. With respect to latitude, negative correlations were observed for PH (r = –0.26) and SF (r = –0.23), and a positive correlation for FI (r = 0.18). With respect to longitude, positive correlations were observed for BA (r = 0.19), DB (r = 0.14), SV (r = 0.25), and SB (r = 0.28), while NB showed a negative correlation (r = –0.28). With respect to altitude, positive correlations were observed for DBH (r = 0.21), SF (r = 0.16), FI (r = 0.13), NB (r = 0.22), and DB (r = 0.15), as well as negative correlations for SV (r = –0.27) and SI (r = –0.19) (Figure 20 – panel B).

In the Padeș provenance trial, correlations between the analysed traits and geographic gradients were generally weak. With respect to latitude, negative correlations were observed for DBH (r = –0.11), HT (r = –0.10), PH (r = –0.08), and SF (r = –0.11), and positive correlations for FI (r = 0.08) and BA (r = 0.06). With respect to longitude, positive correlations were observed for HT (r = 0.21), PH (r = 0.25), SV (r = 0.20), SI (r = 0.24), and SB (r = 0.18), while negative correlations were identified for SF (r = –0.07) and FI (r = –0.07). With respect to altitude, negative correlations were observed for PH (r = –0.19), FI (r = –0.16), DB (r = –0.11), SV (r = –0.28), and SI (r = –0.20) (Figure 20 – panel C).

4.6.1. Discussion on phenotypic and geographic correlations

Phenotypic correlations highlight the integration of growth traits, wood quality, and adaptability, shaped by the interaction between genetic potential and local conditions. In all provenance trials, the strongest correlations were observed between DBH and HT, with the highest intensity at Aleșd and lower values at Făget and Padeș.

At Aleșd, positive correlations among growth traits, wood quality, and survival indicate a linkage between performance and adaptability, while negative correlations suggest trade-offs between growth and stem quality (Macdonald and Hubert 2002). At Făget, correlations are moderate, and negative relationships suggest that poorer stem quality may be associated with lower survival. At Padeș, relationships are more heterogeneous, and growth is not always associated with survival.

Overall, correlation intensity is highest at Aleșd, intermediate at Făget, and lowest at Padeș, highlighting the influence of site conditions (Macdonald and Hubert 2002). Crown-related traits are important for wood quality and can be used in selection (Osborne and Maguire 2016; Briggs et al. 2007), while relationships between growth and wood density indicate a trade-off between productivity and strength (El-Kassaby et al. 2011; Howe et al. 2006).

Correlations with geographic gradients vary across trials: Aleșd exhibits the strongest, Făget the moderate, and Padeș the weakest. In general, latitude, longitude, and altitude influence the analysed traits, reflecting the differential adaptation of provenances to ecological conditions (Climent et al. 2024; Liao et al. 2024; Georgieva et al. 2024).

4.9. Transfer functions under the climatic conditions of the test sites

Provenance performance is influenced by differences between the climatic conditions of the place of origin and those of the test site (ΔC = C_test – C_origin). Transfer functions describe the relationship between tree growth and climatic differences, providing a useful tool for assessing provenance adaptability and identifying thresholds or optimal zones.

Tab. 10 Transfer function models for diameter at 1.30 m (DBH)

Trial	Model	Adj. R^2	Partial R^2	
			Factor 1	Factor 2
Aleșd	38.16 – 0,44 BIO8* + 14.97 SPI03*	0.19**	0.29	0.29
Făget	29.15 – 0,09 AHM* – 8.77 SPI01*	0.16 *	0.14	0.12
Padeș	30.41 + 10,10 SPI09 – 0.34 BIO3	0.12 *	0.14	0.11

Note: *p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); BIO8 – mean temperature of the wettest quarter (°C); SPI03 – standardized precipitation index over 3 months (index); AHM – annual heat–moisture index (°C/mm); SPI01 – standardized precipitation index over 1 month (index); SPI09 – standardized precipitation index over 9 months (index); BIO3 – isothermality (index); Adj. R^2 – proportion of variance explained by the model; Partial R^2 – proportion of total variance explained by a predictor.*

The transfer function models for diameter at 1.30 m (DBH) were significant in all three provenance trials (Table 10). In the Aleșd provenance trial, the model explained 19% of the total variation (Adj. R^2 = 0.19; p ≤ 0.01), and the contribution of each predictor to the explained variation was 0.29. In the Făget provenance trial, the model explained 16% of the variance (Adj. R^2 = 0.16; p ≤ 0.05), with R^2 values of 0.14 and 0.12 for the two included predictors. In the Padeș provenance trial, the model explained 12% of the variation in DBH (Adj. R^2 = 0.12; p ≤ 0.05), with R^2 values of 0.14 and 0.11 for the two included predictors.

Tab. 11 Transfer function models for total height (HT)

Trial	Model	Adj. R^2	Partial R^2	
			Factor 1	Factor 2
Aleșd	33.17 – 0.33 BIO8* – 15.19 SPEI06	0.23**	0.45	0.30

Făget	28.42 +10.95 SPEI08* – 0.02 bFFP	0.10*	0.18	0.8
Padeș	28.04 + 0.04 AHM – 0.13 BIO3	0.16 *	0.14	0.12

Note: *p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); BIO8 – mean temperature of the wettest quarter (°C); SPEI06 – standardized precipitation evapotranspiration index over 6 months (index); SPEI08 – standardized precipitation evapotranspiration index over 8 months (index); BFFP – frost-free period (days); AHM – annual heat–moisture index (°C/mm); BIO3 – isothermality (index); Adj. R² – proportion of variance explained by the model; Partial R² – proportion of total variance explained by a predictor.*

The transfer function models for total height (HT) were significant in all three provenance trials (Table 11). In the Aleșd provenance trial, the model explained 23% of the total variation (Adj. R^2 = 0.23; p ≤ 0.01), with R^2 values of 0.45 and 0.30 for the two included predictors. In the Făget provenance trial, the model explained 10% of the variance (Adj. R^2 = 0.10; p ≤ 0.05), with R^2 values of 0.18 and 0.08 for the two included predictors. In the Padeș provenance trial, the model explained 16% of the variation in HT (Adj. R^2 = 0.16; p ≤ 0.05), with R^2 values of 0.14 and 0.12 for the two included predictors.

Tab. 12 Transfer function models for survival (SV)

Trial	Model	adj. R^2	Partial R^2
Aleșd	14.31 – 1.06 BIO6***	0.36***	0.38
Făget	12.20 – 0.01BIO13 **	0.15*	0.24
Padeș	13.44 – 0.004 BIO19*	0.10*	0.14

Note: *p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); BIO6 – minimum temperature of the coldest month (°C); BIO13 – precipitation of the wettest month (mm); BIO19 – precipitation of the coldest quarter (mm); Adj. R² – proportion of variance explained by the model; Partial R² – proportion of total variance explained by a predictor.*

The transfer function models for survival (SV) were significant in all three provenance trials (Table 12). In the Aleșd provenance trial, the model explained 36% of the total variation (Adj. R^2 = 0.36; p ≤ 0.001), with a predictor R^2 value of 0.38. In the Făget provenance trial, the model explained 15% of the variance (Adj. R^2 = 0.15; p ≤ 0.01), with a predictor R^2 of 0.24. In the Padeș provenance trial, the model explained 14% of SV variation (Adj. R^2 = 0.14; p ≤ 0.05), with a predictor R^2 value of 0.14.

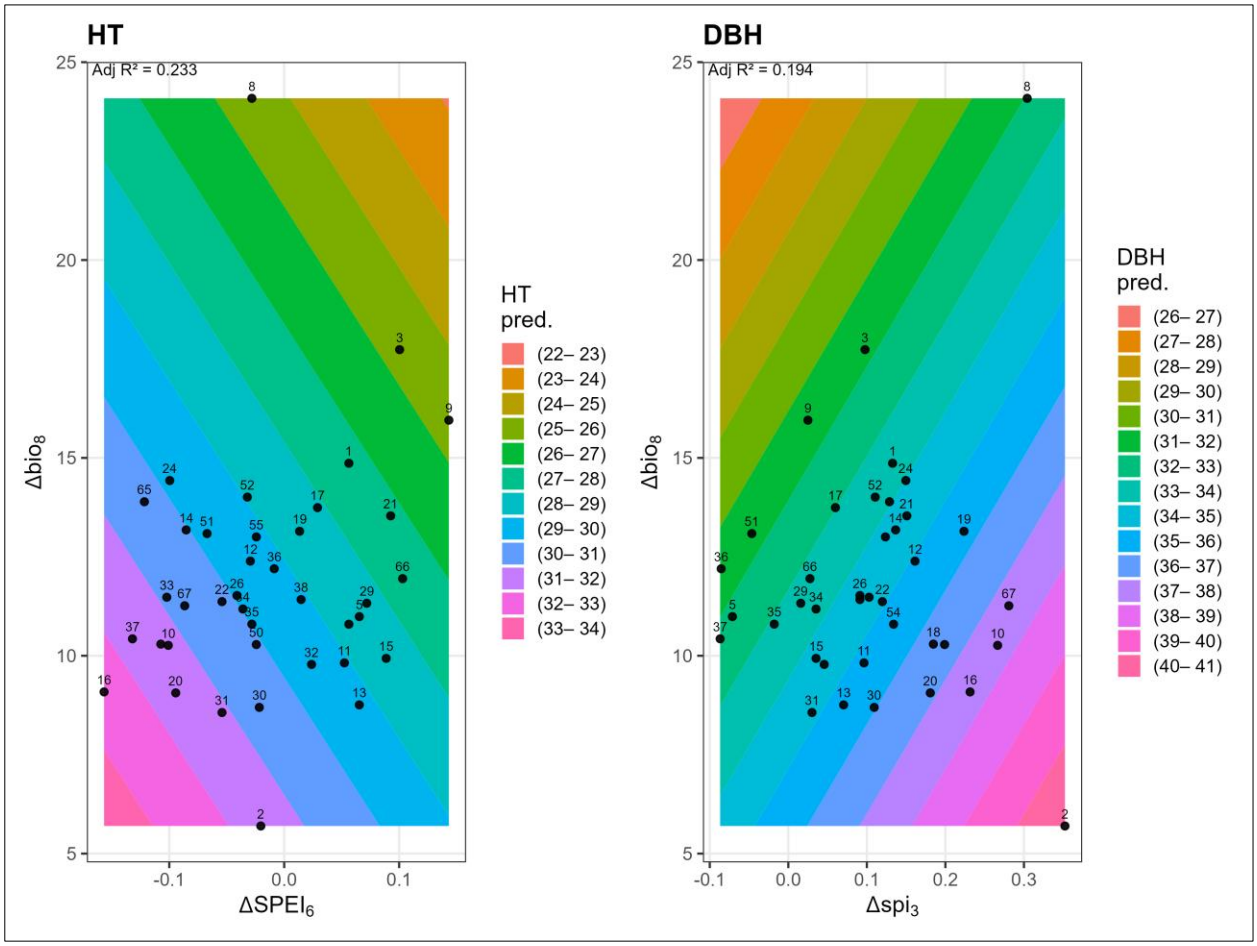

Fig. 21 Transfer functions for total height (HT) and diameter at 1.30 m (DBH) as a function of climatic differences between the place of origin and Aleșd

Note: *The figure illustrates the transfer functions for HT and DBH for Douglas-fir provenances tested in the Aleșd provenance trial. In the left panel, HT is modelled as a function of ΔSPEI6 and ΔBIO8 (Adj. R^2 = 0.23), while in the right panel, DBH is modelled as a function of ΔSPI3 and ΔBIO8 (Adj. R^2 = 0.19). The colored bands indicate the predicted values of HT and DBH, and the black points correspond to the observed provenance values.*

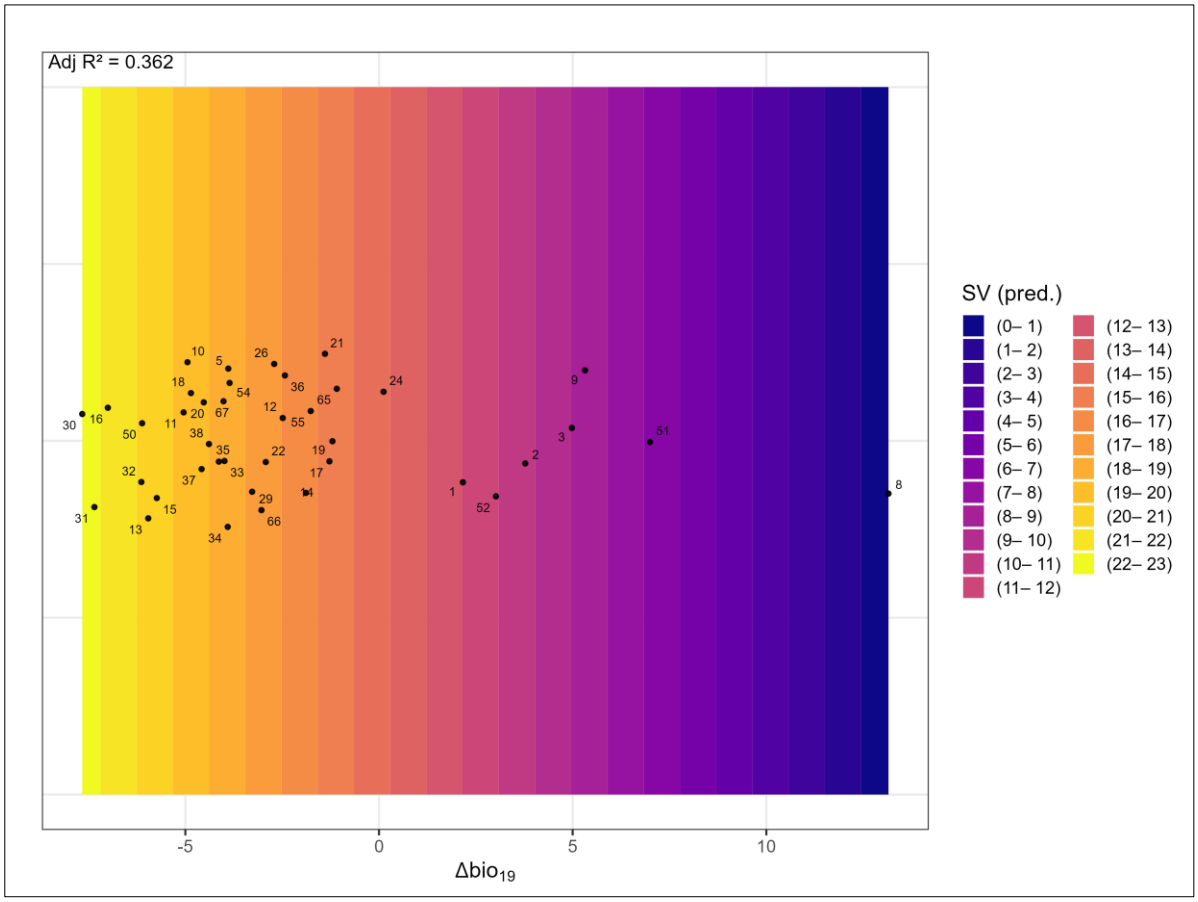

Fig. 22 Univariate transfer function for survival (SV) as a function of climatic differences between the place of origin and Aleșd

Note: *The figure illustrates the univariate transfer function for SV for Douglas-fir provenances tested in the Aleșd provenance trial in relation to ΔBIO19 (Adj. R² = 0.36). The colored bands indicate the predicted values of SV, and the black points correspond to the observed provenance values.*

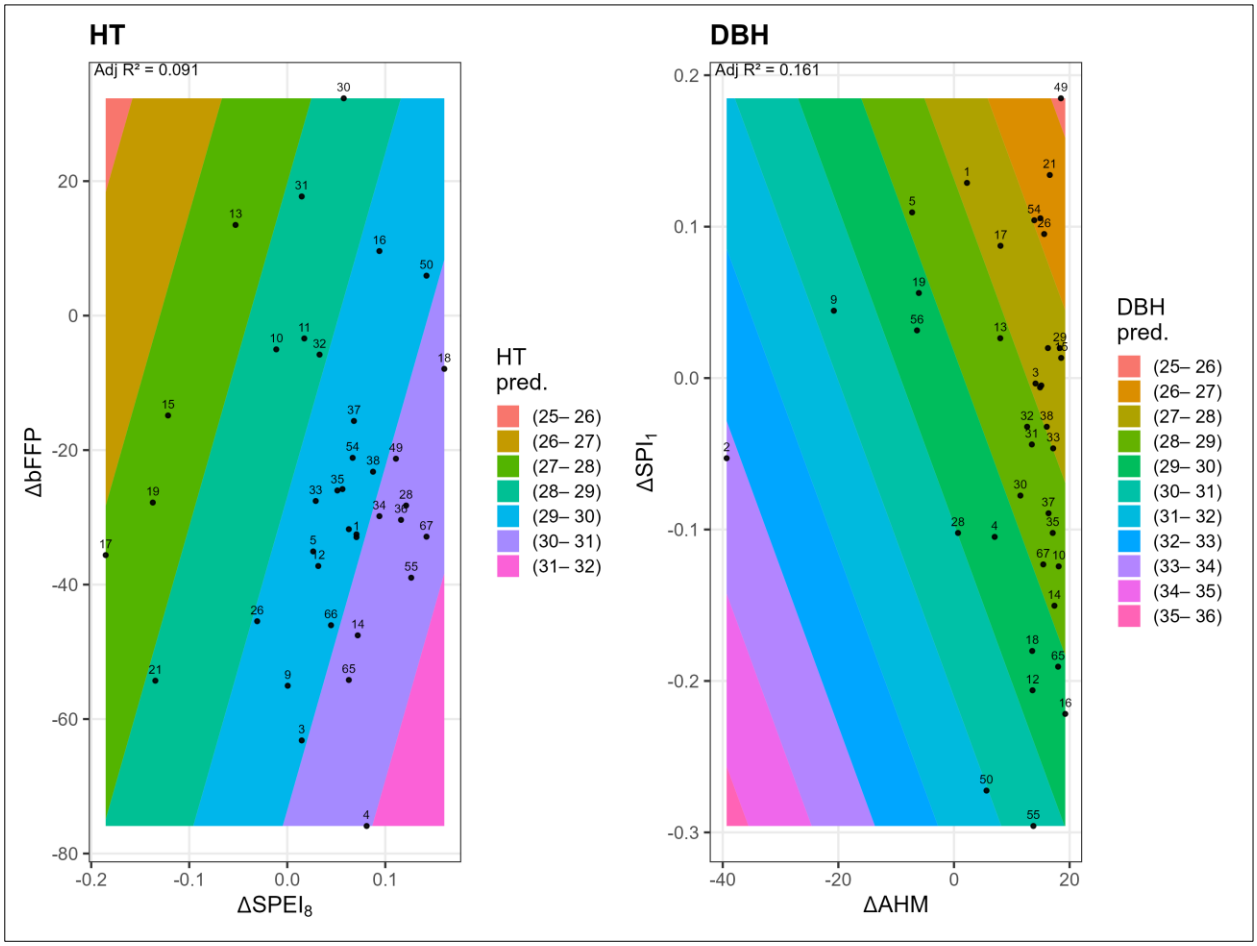

Fig. 23 Transfer functions for total height (HT) and diameter at 1.30 m (DBH) as a function of climatic differences between the place of origin and Făget

Note: *The figure illustrates the transfer functions for HT and DBH for Douglas-fir provenances tested in the Făget provenance trial. In the left panel, HT is modelled as a function of ΔSPEI8 and ΔbFFP (Adj. R^2 = 0.10), while in the right panel, DBH is modelled as a function of ΔAHM and ΔSPI1 (Adj. R^2 = 0.16). The colored bands indicate the predicted values of HT and DBH, and the black points correspond to the observed provenance values.*

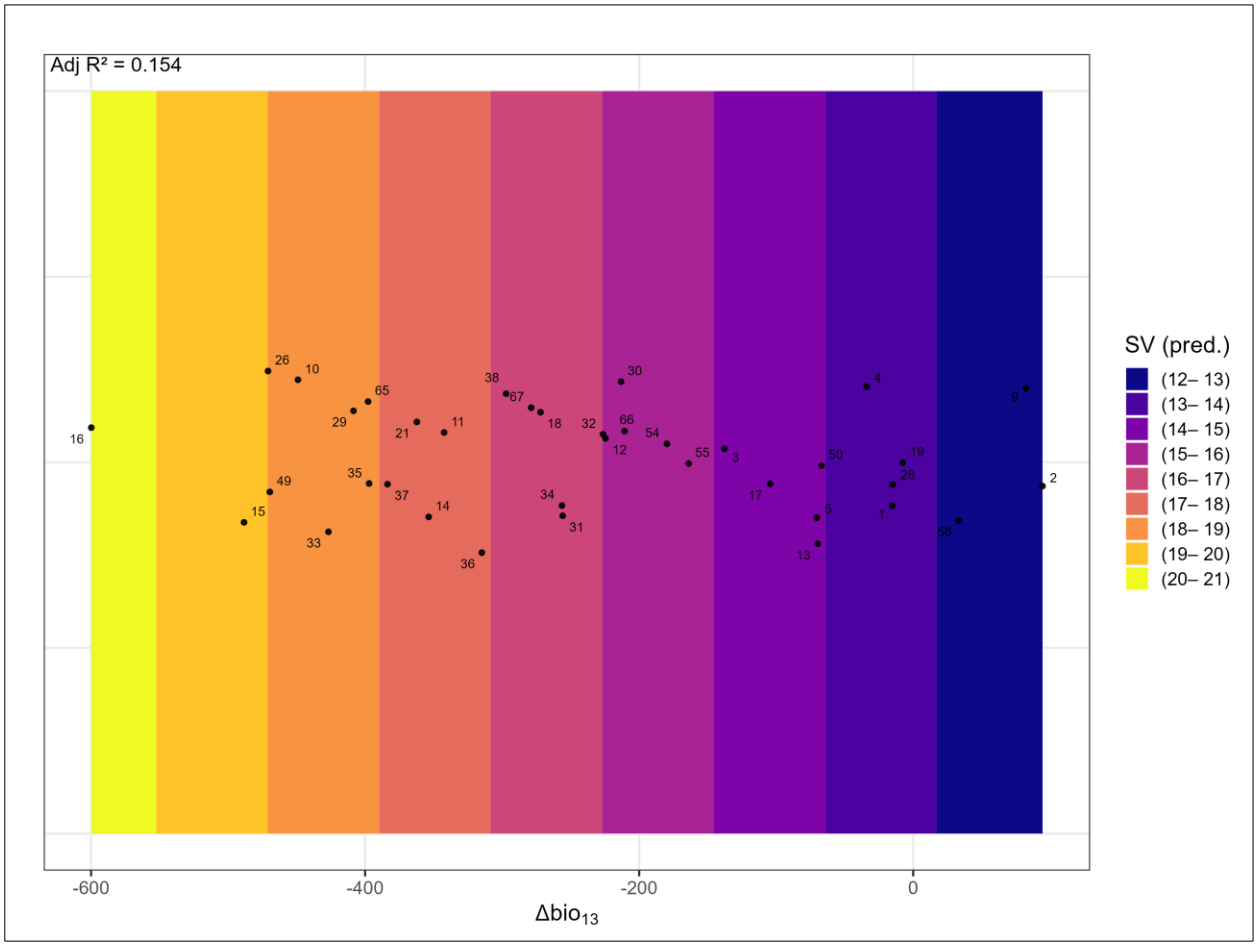

Fig. 24 Univariate transfer function for survival (SV) as a function of climatic differences between the place of origin and Făget

Note: *The figure illustrates the univariate transfer function for SV for Douglas-fir provenances tested in the Făget provenance trial in relation to ΔBIO13 (Adj. R² = 0.15). The colored bands indicate the predicted values of SV, and the black points correspond to the observed provenance values.*

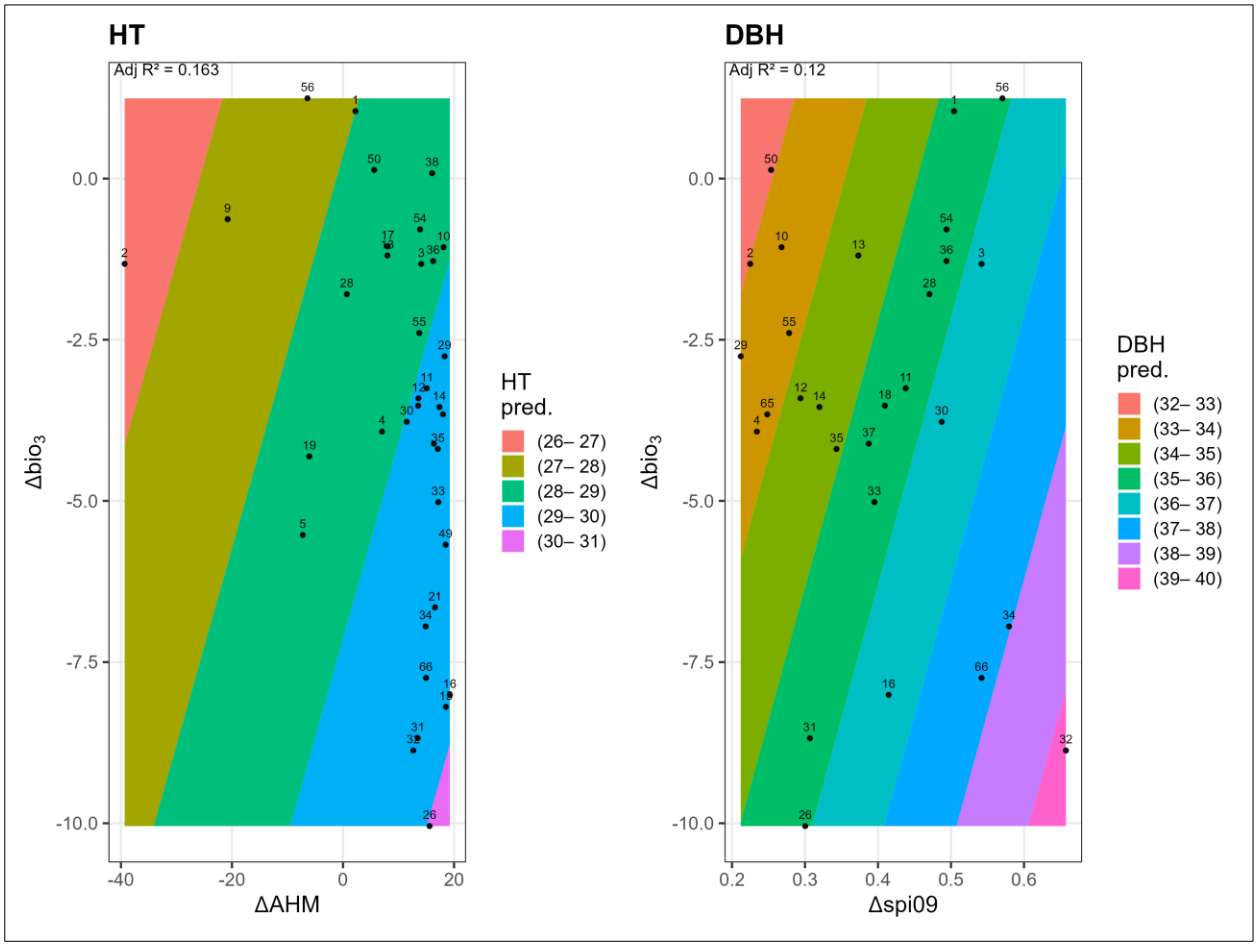

Fig. 25 Transfer functions for total height (HT) and diameter at 1.30 m (DBH) as a function of climatic differences between the place of origin and Padeș

Note: *The figure illustrates the transfer functions for HT and DBH for Douglas-fir provenances tested in the Padeș provenance trial. In the left panel, HT is modelled as a function of ΔAHM and ΔBIO3 (Adj. R^2 = 0.16), while in the right panel, DBH is modelled as a function of ΔSPI09 and ΔBIO3 (Adj. R^2 = 0.12). The colored bands indicate the predicted values of HT and DBH, and the black points correspond to the observed provenance values.*

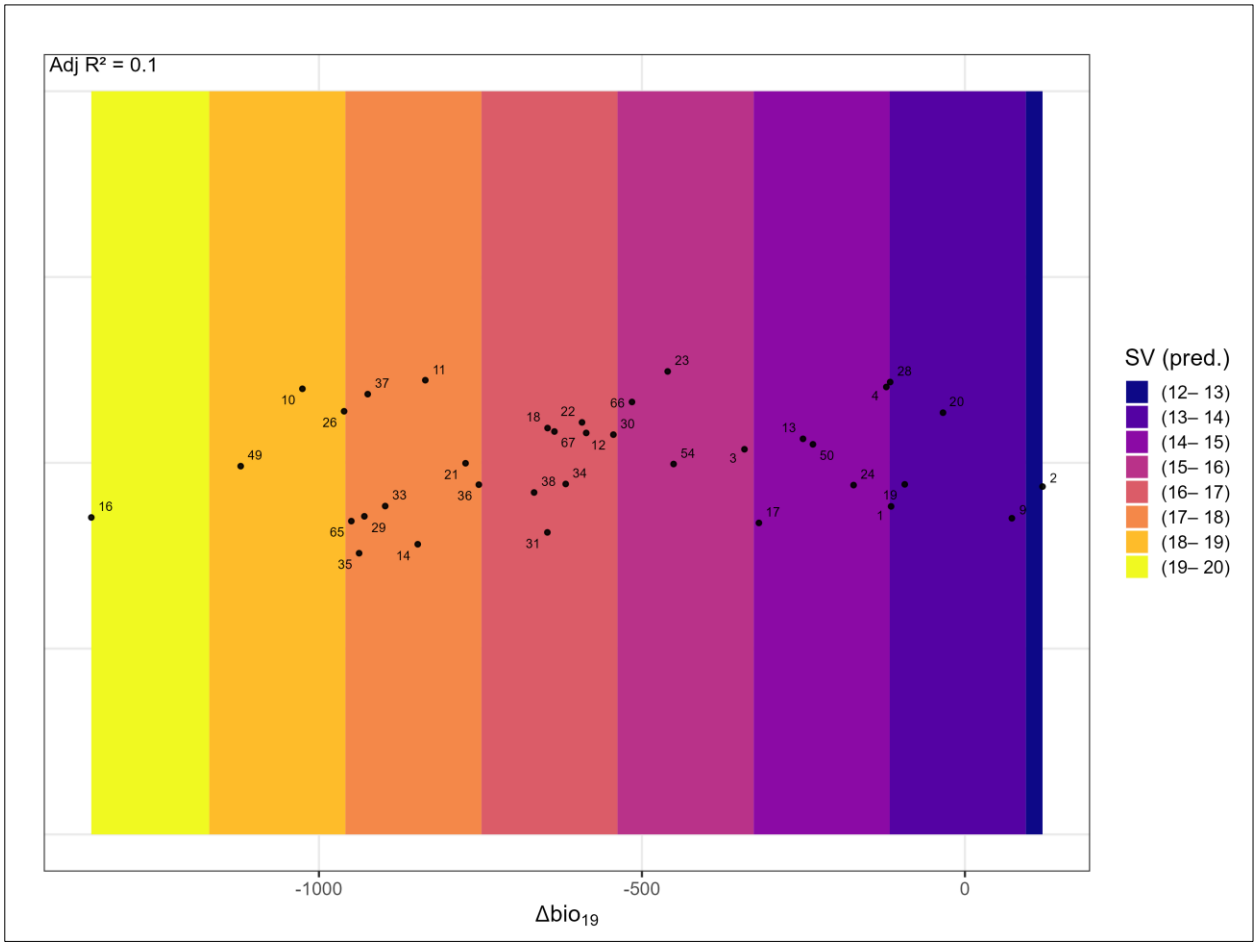

Fig. 26 Univariate transfer function for survival (SV) as a function of climatic differences between the place of origin and Padeș

Note: *The figure illustrates the univariate transfer function for SV for Douglas-fir provenances tested in the Padeș provenance trial in relation to ΔBIO19 (Adj. R² = 0.10). The colored bands indicate the predicted values of SV, and the black points correspond to the observed provenance values.*

4.9. Response functions to the climatic conditions of the test sites

To assess the sensitivity of Douglas-fir provenances to the climatic conditions at each test site, response functions were developed that describe the relationships between HT, DBH, and SV and the test-site climatic variables. Unlike transfer functions, which incorporate climatic differences between the place of origin and the test site, response functions analyze the influence of the test site climate on provenance performance.

Tab. 13 Response function models for diameter at 1.30 m (DBH)

Trial	Model	Adj. R^2	Partial R^2	
			Factor 1	Factor 2
Aleșd	27.84 + 0.35 BIO9* – 14.87 SPEI03*	0.18**	0.15	0.13

Făget	28.84 + 5.16 SPEI02 – 191.51 $SPEI02^{2*}$ + 10.79 SPEI03 + 74,42 $SPEI03^{2**}$	0.21*	0.21	0.19
Padeș	34 – 10.11 SPI09	0.9*	0.15	

Note: *p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); BIO9 – mean temperature of the driest quarter (°C); SPEI02 – standardized precipitation evapotranspiration index over 2 months (index); SPEI03 – standardized precipitation evapotranspiration index over 3 months (index); SPI09 – standardized precipitation index over 9 months (index); Adj. R^2 – proportion of variance explained by the model; Partial R^2 – proportion of total variance explained by a predictor.*

The response function models for diameter at 1.30 m (DBH) were significant in all three provenance trials (Table 13). In the Aleșd provenance trial, the model explained 18% of the total variation (Adj. R^2 = 0.18; p ≤ 0.01), with R^2 values of 0.15 and 0.13 for the two included predictors. In the Făget provenance trial, the model explained 21% of the variance (Adj. R^2 = 0.21; p ≤ 0.05), with R^2 values of 0.21 and 0.19 for the two included predictors. In the Padeș provenance trial, the model explained 9% of the variation in DBH (Adj. R^2 = 0.09; p ≤ 0.05), with a predictor R^2 of 0.15.

Tab. 14 Response function models for total height (HT)

Trial	Model	Adj. R^2	Partial R^2	
			Factor 1	Factor 2
Aleșd	27.28 + 0.43 BIO8** – 11.55 SPI03*	0.25 **	0.12	0.11
Făget	28.34 – 10.45 SPEI08 + 16.74 SPEI02* – 160.91 $SPEI02^{2*}$	0.19 *	0.17	0.16
Padeș	-20.80 + 3.69 BIO5** – 0.06 $BIO5^{2**}$	0.21 **	0.25	

Note: *p ≤ 0.05 (*), p ≤ 0.01 (**), and p ≤ 0.001 (***); BIO8 – mean temperature of the wettest quarter (°C); SPI03 – standardized precipitation index over 3 months (index); SPEI08 – standardized precipitation evapotranspiration index over 8 months (index); SPEI02 – standardized precipitation evapotranspiration index over 2 months (index); BIO5 – maximum temperature of the warmest month (°C); Adj. R^2 – proportion of variance explained by the model; Partial R^2 – proportion of total variance explained by a predictor.*

The response function models for total height (HT) were significant in all three provenance trials (Table 14). In the Aleșd provenance trial, the model explained 25% of the total variation (Adj. R^2 = 0.25; p ≤ 0.01), with R^2 values of 0.12 and 0.11 for the two included predictors. In the Făget provenance trial, the model explained 19% of the variance (Adj. R^2 = 0.19; p ≤ 0.05), with R^2 values of 0.17 and 0.16 for the two included predictors. In the Padeș provenance trial, the model explained 21% of the variation in HT (Adj. R^2 = 0.21; p ≤ 0.01), with a predictor R^2 of 0.25.

Tab. 15 Response function models for survival (SV)

Trial	Model	Adj. R^2	Partial R^2	
			Factor 1	Factor 2
Aleșd	19.05 + 0.96 BIO6*** + 35.34 SPEI06**	0.47 ***	0.36	0.19
Făget	12.98 + 0.002 BIO12* + 19.66 SPEI05	0.29 **	0.37	0.30
Padeș	3.85 + 0.04 SHM* + 0.004 BIO12**	0.19 *	0.18	0.15

Note: *$p \leq 0.05$ (*), $p \leq 0.01$ (**), and $p \leq 0.001$ (***); BIO6 – minimum temperature of the coldest month (°C); SPEI06 – standardized precipitation evapotranspiration index over 6 months (index); BIO12 – mean annual precipitation (mm); SPEI05 – standardized precipitation evapotranspiration index over 5 months (index); SHM – summer heat–moisture index (°C/mm); Adj. R^2 – proportion of variance explained by the model; Partial R^2 – proportion of total variance explained by a predictor.*

The response function models for survival (SV) were significant in all three provenance trials (Table 15). In the Aleșd provenance trial, the model explained 36% of the total variation (Adj. $R^2 = 0.36$; $p \leq 0.001$), with R^2 values of 0.36 and 0.19 for the two included predictors. In the Făget provenance trial, the model explained 29% of the variance (Adj. $R^2 = 0.29$; $p \leq 0.01$), with R^2 values of 0.37 and 0.30 for the two included predictors. In the Padeș provenance trial, the univariate model explained 19% of the variation in SV (Adj. $R^2 = 0.19$; $p \leq 0.05$), with R^2 values of 0.18 and 0.15 for the included predictors.

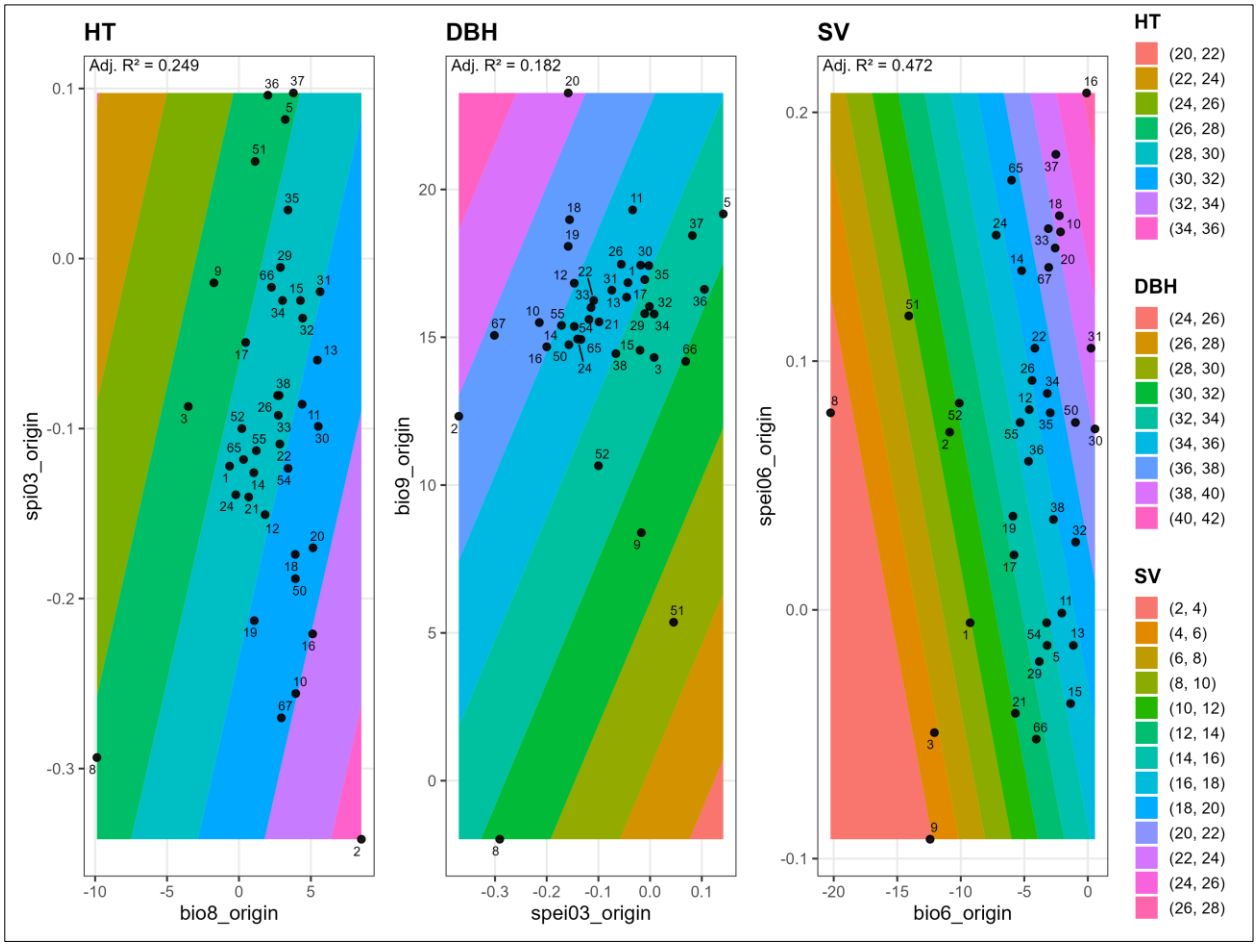

Fig. 27 Response functions for total height (HT), diameter at 1.30 m (DBH), and survival (SV) as a function of the climatic conditions of the place of origin and Aleșd

Notă: *The figure illustrates the response functions for HT, DBH, and SV for Douglas-fir provenances tested in the Aleșd provenance trial. In the left panel, HT is modelled as a function of BIO8 and SPI03 (Adj. R^2 = 0.24). In the middle panel, DBH is modelled as a function of SPEI03 and BIO9 (Adj. R^2 = 0.18). In the right panel, SV is modelled as a function of BIO6 and SPEI06 (Adj. R^2 = 0.47). The colored bands indicate the predicted values of HT, DBH, and SV, and the black points correspond to the observed provenance values.*

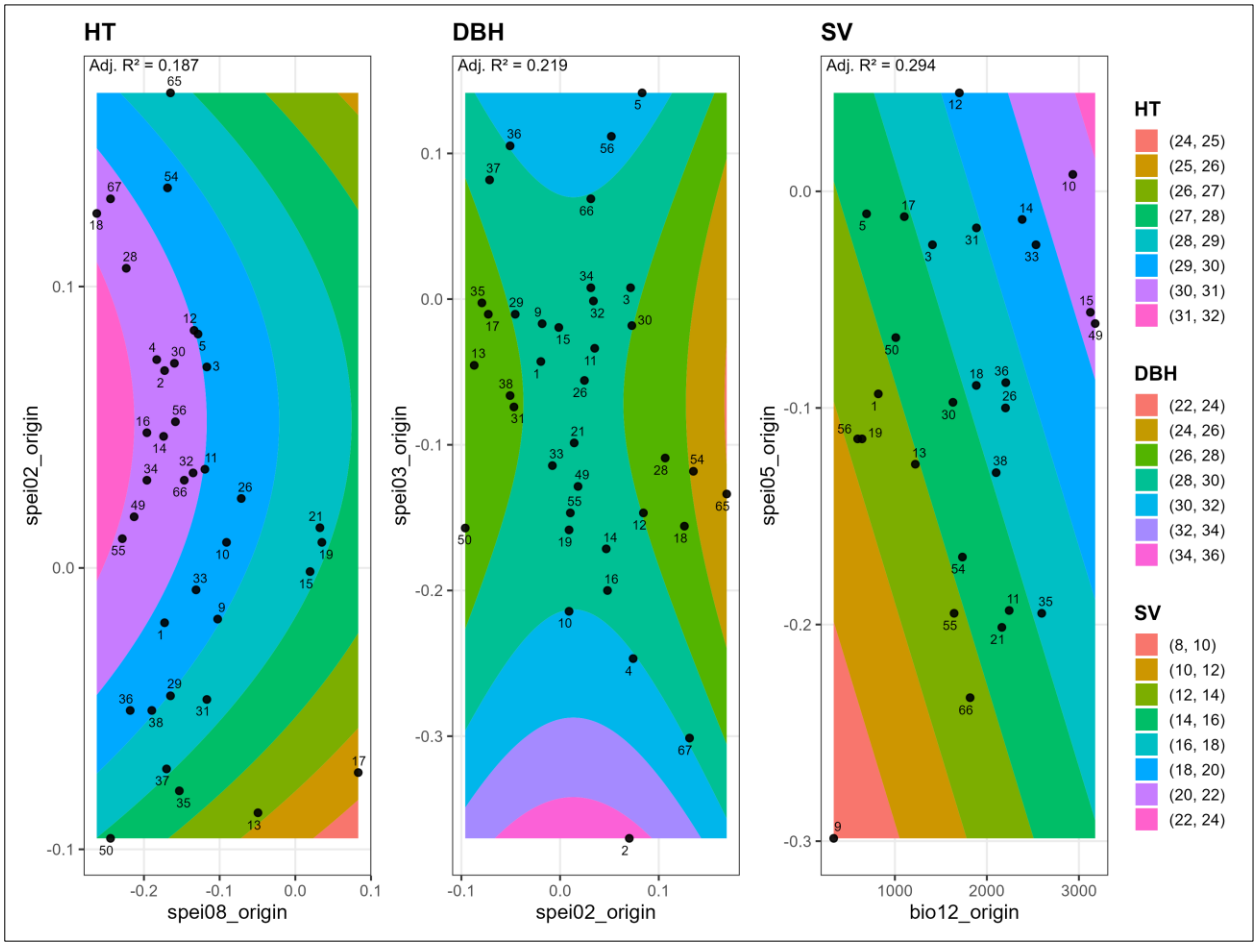

Fig. 28 Response functions for total height (HT), diameter at 1.30 m (DBH), and survival (SV) as a function of the climatic conditions of the place of origin and Făget

Note: *The figure illustrates the response functions for HT, DBH, and SV for Douglas-fir provenances tested in the Făget provenance trial. In the left panel, HT is modelled as a function of SPEI08 and SPI02 (Adj. R^2 = 0.18). In the middle panel, DBH is modelled as a function of SPEI02 and SPEI03 (Adj. R^2 = 0.21). In the right panel, SV is modelled as a function of BIO12 and SPEI05 (Adj. R^2 = 0.29). The colored bands indicate the predicted values of HT, DBH, and SV, and the black points correspond to the observed provenance values.*

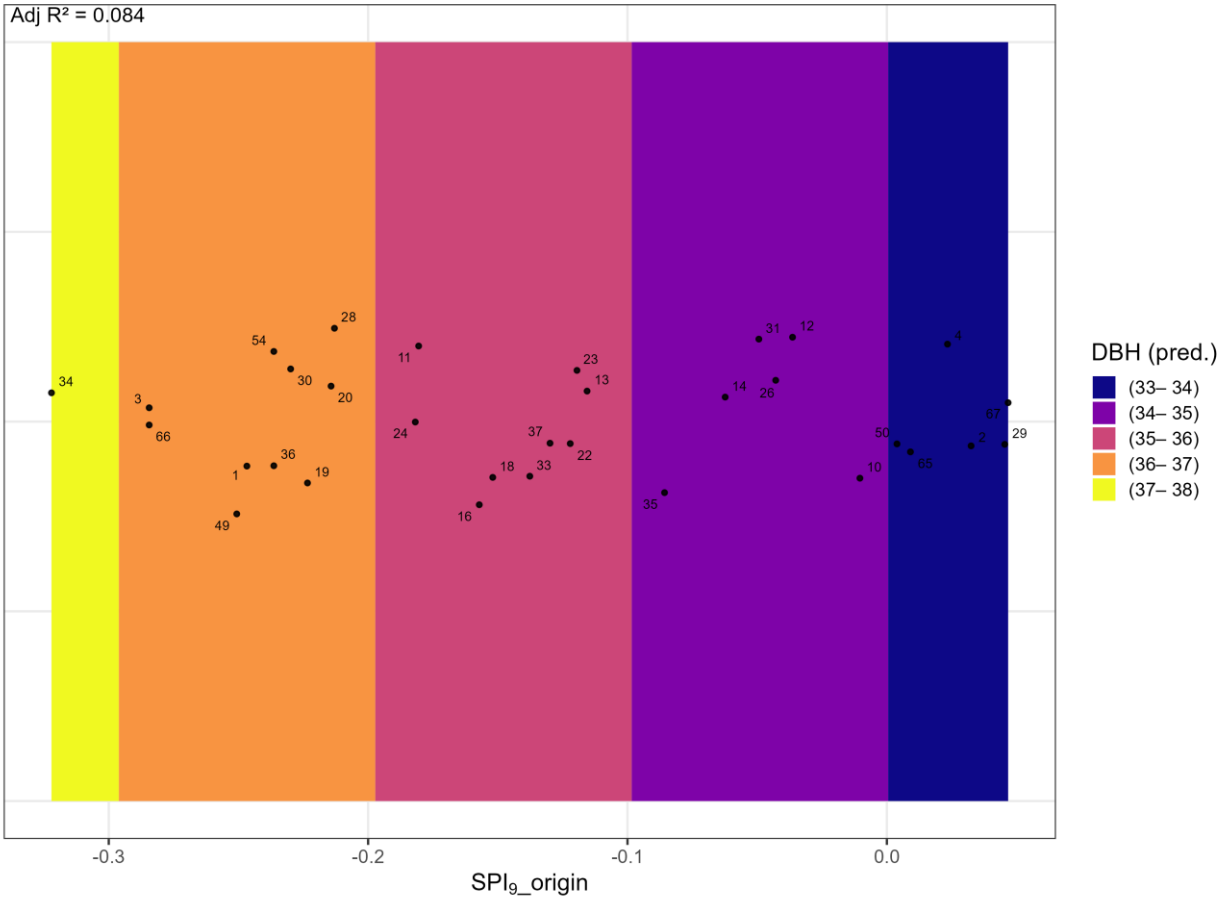

Fig. 29 Univariate response function for diameter at 1.30 m (DBH) as a function of the climatic conditions of the place of origin and Padeș

Note: *The figure illustrates the univariate response function for DBH for Douglas-fir provenances tested in the Padeș provenance trial in relation to SPI03 (Adj. R² = 0.08). The coloured bands indicate the predicted DBH values, and the black points correspond to the observed provenance values.*

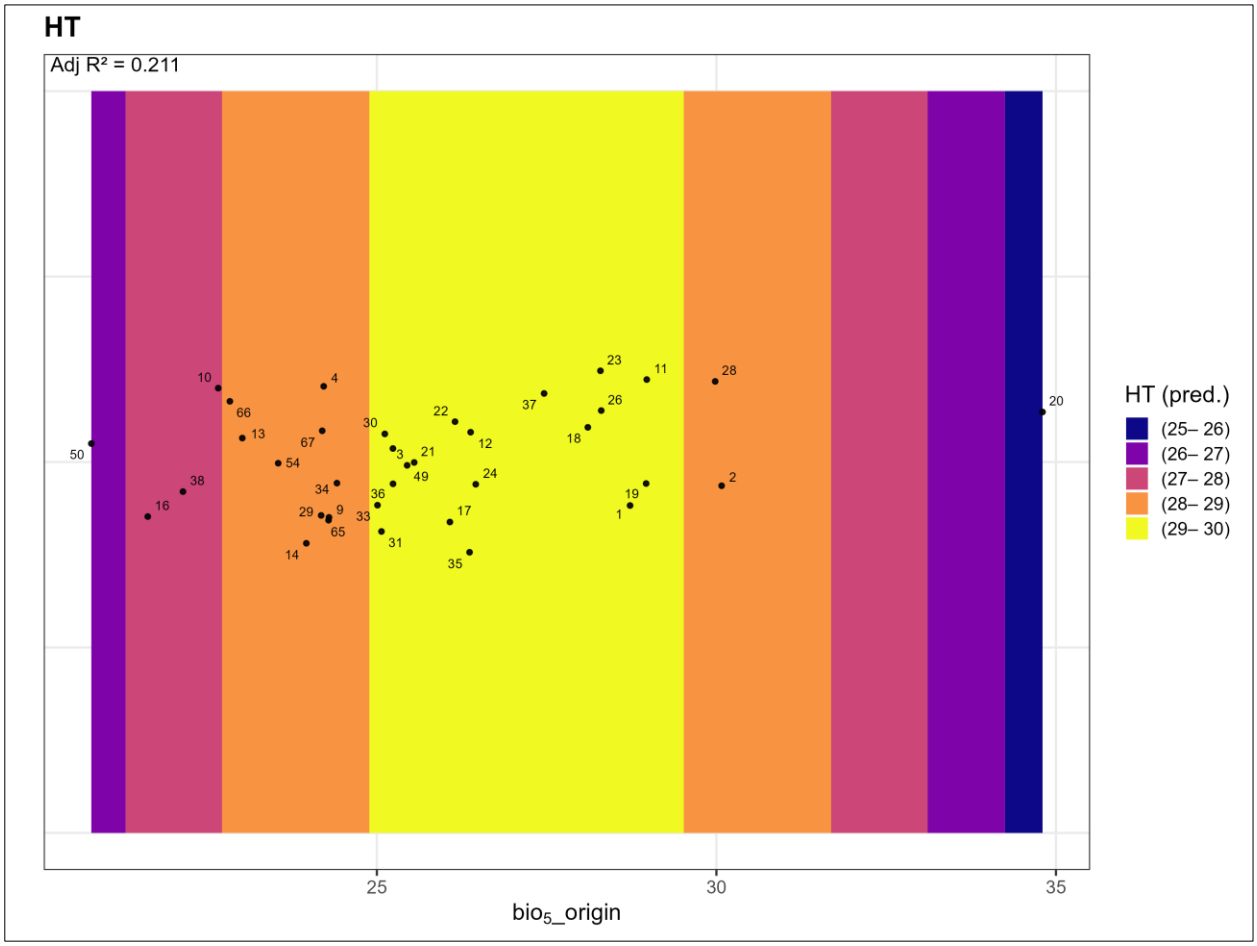

Fig. 30 Univariate response function for total height (HT) as a function of the climatic conditions of the place of origin and Padeș

Note: *The figure illustrates the univariate response function for HT for Douglas-fir provenances tested in the Padeș provenance trial in relation to BIO4 (Adj. R² = 0.21). The coloured bands indicate the predicted HT values, and the black points correspond to the observed provenance values.*

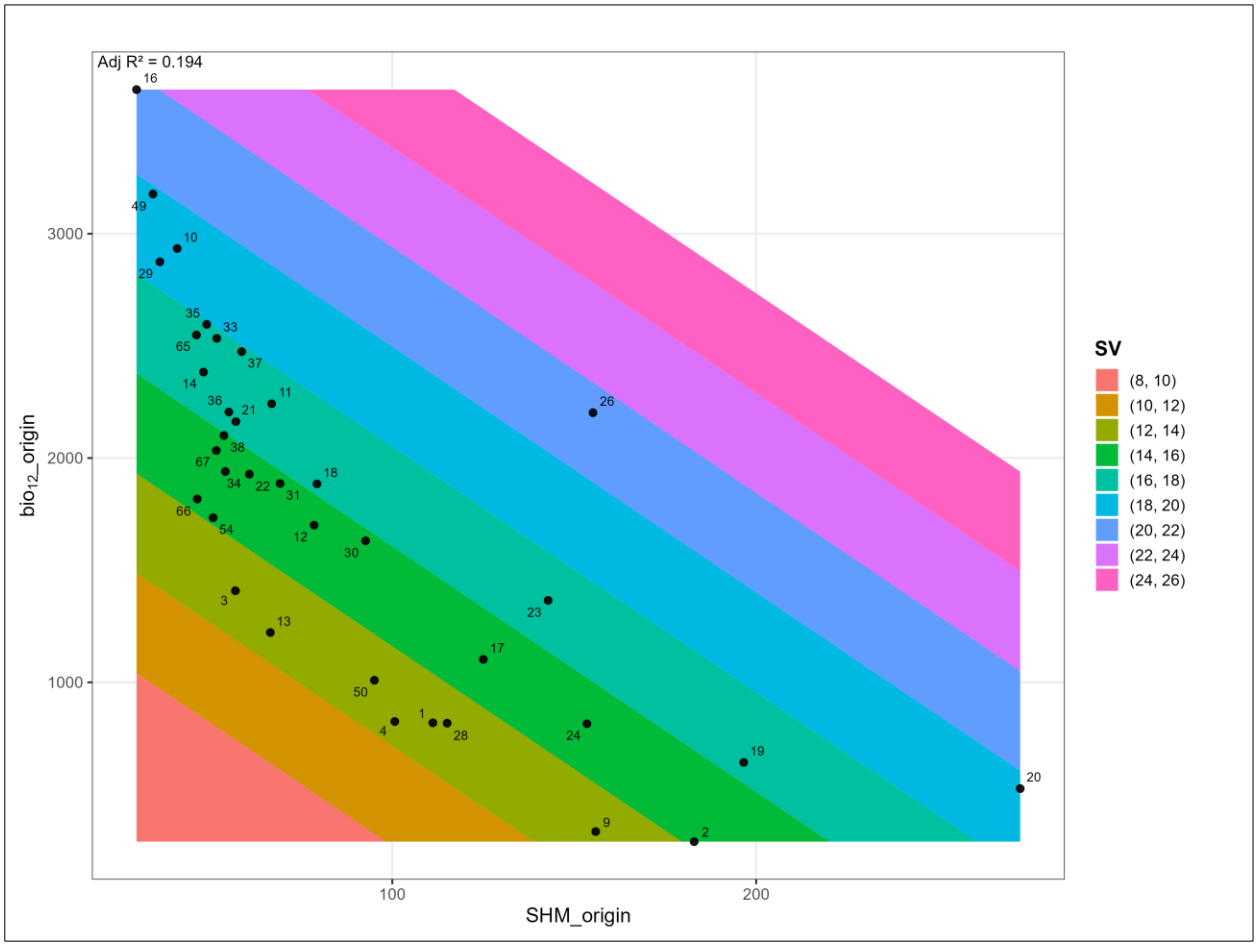

Fig. 31 Response function for survival (SV) as a function of the climatic conditions of the place of origin and Padeș

Note: *The figure illustrates the response functions for SV for Douglas-fir provenances tested in the Padeș provenance trial, modelled as a function of SHM and BIO12 (Adj. R^2 = 0.19). The colored bands indicate the predicted values of SV, and the black points correspond to the observed provenance values.*

4.9.1 Discussion on transfer and response functions Discussion on transfer and response functions

Douglas-fir exhibits high genetic variability across climatic gradients, and provenances are adapted to their climate of origin, as reflected in variation in growth and adaptive traits (Leites et al. 2012; Neophytou et al. 2016; St. Clair et al. 2005; St. Clair et al. 2007; St. Clair et al. 2020).

In Europe, Douglas-fir performance depends on the climatic matching between provenance and test site. The species is considered promising under climate change scenarios, but sensitive to drought and extreme temperatures (Bansal et al. 2015; Niemczyk et al. 2021; Dyderski et al. 2018). Coastal provenances have generally shown superior performance under conditions similar to maritime climates, while physiological and genetic differences reflect mechanisms of adaptation and phenotypic plasticity (Espinoza et al. 2023; Hess et al. 2016; Riedel et al. 2025).

Transfer function models indicate a moderate influence of climate on diameter at 1.30 m and total height, and a stronger influence on survival, which is closely related to thermal variables, particularly BIO6 (Leites et al. 2012). At Aleșd, temperature (BIO8) limits growth, while water availability (SPI03) supports it, and minimum winter temperatures determine survival. At Făget, growth is influenced by aridity and water regime (AHM, SPI, SPEI), while survival depends on precipitation (BIO13). At Padeș, the climatic influence is weaker but remains dependent on water availability (SPI09), temperature (BIO3, BIO5), and precipitation (BIO19).

Response function models confirm the influence of test site climatic conditions on provenance performance. At Aleșd, higher temperatures favour growth, but water deficit limits it; at Făget, relationships are nonlinear, with optimal moisture ranges; at Padeș, growth is controlled by water regime and temperature, with optimal values for development.

Overall, survival shows the strongest relationships with climatic variables, followed by total height and diameter at 1.30 m. Provenance responses vary with local conditions, highlighting the provenance × environment interaction and its importance for the selection and use of provenances under future climatic conditions (Chakraborty et al. 2019; Wesselkamp et al. 2024).

5. CONCLUSIONS. PERSONAL CONTRIBUTIONS. DISSEMINATION OF RESULTS. FUTURE RESEARCH DIRECTIONS

5.1. Conclusions

Genetic variability of quantitative traits

- The analysis revealed genetic variability among provenances for the analysed quantitative traits; however, its intensity differs among Douglas-fir provenance trials.
- In the Aleșd provenance trial, the effect of provenance was highly significant for all analysed traits, indicating clear genetic differences among provenances.
- In the Făget provenance trial, genetic variability was significant for all biometric traits (DBH, HT, VOL, SB), although the proportion of genetic variance was low.
- In the Padeș provenance trial, genetic variability was limited, being significant only for total height (HT) and tree volume (VOL), while diameter at 1.30 m (DBH) and basal area (SB) did not show significant differences among provenances.
- In all provenance trials, residual variance had a dominant contribution, indicating a major role of environmental factors in the phenotypic expression of the studied traits.
- Among the analysed quantitative traits, total height (HT) and diameter at 1.30 m (DBH) showed the highest genetic variability among provenances, suggesting greater potential for selection.
- Provenances with the best growth performance originate from western North America (Washington, Oregon, southern British Columbia), as well as from Europe (Germany and France), including Romania (Nădrăgel, Toplița, Vârful Dăii, and Anina–Buhui).
- The genotype × environment interaction is highly significant for all analysed quantitative traits, indicating that provenance performance varies depending on the test site.
- Site had the strongest effect on all traits, highlighting the major influence of environmental conditions on growth performance.
- The effect of provenance was significant for all traits, confirming the existence of genetic differentiation among provenances, although strongly influenced by environmental conditions.

Genetic variability of the main wood quality and adaptive traits

- Genetic variability for wood quality and adaptive traits was generally low, and the influence of the environment was significant across all provenance trials.
- Among the analysed wood quality traits, pruning height (PH) and branch insertion angle (BA) showed the most consistent genetic differentiation among provenances, regardless of the provenance trial.

- Stem form (SF) and forking (FI) did not show significant differences among provenances, indicating high stability of these traits.
- Number of branches (NB) and branch diameter (DB) showed significant differences only at Aleșd and Făget, suggesting moderate sensitivity to environmental conditions.
- The slenderness index (SI) showed differences among provenances at Aleșd and Făget, but not at Padeș, indicating a response dependent on test site conditions.
- Survival (SV) was significantly influenced by provenance only in the Aleșd trial, where genetic differentiation was more pronounced, while in the other trials, environmental influence was predominant.
- The highest survival values were recorded for provenances from the USA (Washington and Oregon), Canada (British Columbia), as well as from Europe (France and Germany), and Romania (Pădurea Neagră, Piatra Albă, Toplița, Vârful Dăii, Nădrăgel, and Anina–Buhui).
- The influence of the test site was generally stronger than that of provenance, highlighting the determining role of site conditions.
- The genotype × environment interaction was limited, showing a significant effect only for branch diameter (DB) and slenderness index (SI), indicating relatively stable performance of provenances for most analysed traits.
- Overall, only certain traits—pruned height (PH), branch insertion angle (BA), and survival (SV) in the Aleșd provenance trial—show potential for selection, although this is strongly conditioned by the test site.

Selection of the best provenances using the MGIDI and MTSI selection indices

- The use of multivariate indices MGIDI and MTSI enabled the identification of Douglas-fir provenances with superior performance, demonstrating their usefulness in the selection process.
- In all provenance trials, the provenances selected using MGIDI showed mean values higher than the trial averages.
- The highest gains obtained through MGIDI selection were observed for survival (SV), with differences of up to 28.1% at Aleșd, 15.1% at Făget, and 9.6% at Padeș, indicating a high potential for improving adaptability.
- Gains for diameter at 1.30 m (DBH) were consistent, with maximum differences of 11.1% at Aleșd, 8.3% at Făget, and 2% at Padeș.
- For total height (HT), the differences obtained through MGIDI ranged between 0 and 7.4%.

- The provenances selected through MGIDI originate from diverse geographic regions, including North America (USA, Canada) and Europe (Germany, France, Romania).
- Selection based on the MTSI index resulted in a group of eight provenances considered optimal across all test sites, originating from North America (USA, Canada) and Europe (France, Germany, and Romania).
- Compared to MGIDI, the percentage differences for diameter at 1.30 m (DBH) and total height (HT) obtained with MTSI are more moderate, but very high gains were recorded for survival (SV), up to 35% at Aleșd, 22.3% at Făget, and 20.2% at Padeș.
- Provenance 58 – Piatra Albă (Aleșd Forest District) was selected using the MTSI index as the most performant and stable across all three Douglas-fir provenance trials.
- Overall, the results highlight that multivariate selection allows the identification of high-performing and stable provenances for use in breeding programs and afforestation.

Phenotypic correlations among the analyzed traits

- In all provenance trials, strong positive correlations were observed between diameter at 1.30 m (DBH) and total height (HT).
- DBH and HT also showed moderate positive correlations with branch diameter (DB) and pruning height (PH), suggesting that larger trees tend to develop thicker branches and higher pruning height.
- Positive correlations between total height (HT) and pruning height (PH) were significant in all trials, indicating that more vigorous trees tend to have higher pruning height.
- Survival (SV) was positively correlated with total height (HT) and pruning height (PH) in the Aleșd trial and with stem form (SF) in the Făget trial, suggesting that provenances with greater height or better stem form may have higher adaptability under certain environmental conditions.
- In the Padeș trial, the negative correlation between diameter at 1.30 m (DBH) and survival (SV) indicates a possible trade-off between growth and survival under more limiting environmental conditions.
- Stem form (SF) and forking (FI) showed consistent negative correlations across all provenance trials, indicating that provenances with forked stems also exhibit form defects.
- Branch insertion angle (BA) was negatively correlated with survival (SV) at Aleșd, suggesting that certain wood quality traits may influence adaptability.

- Overall, phenotypic correlations indicate that selection for growth may indirectly influence certain wood quality traits; however, the direction and strength of these relationships depend on the test site.

Correlations between the analysed traits and the geographic gradients of origin

- Relationships between the analysed traits and the geographic gradients of origin (latitude, longitude, and altitude) varied among provenance trials, indicating responses dependent on local environmental conditions.
- The Aleșd provenance trial showed the most significant correlations with geographic gradients, indicating a stronger influence of geographic origin on the analysed traits.
- Longitude of origin was the most frequently correlated gradient with growth and adaptability traits, especially in the Aleșd and Făget trials, highlighting the influence of climatic differences between eastern and western regions of provenance origin.
- Altitude of origin was significantly correlated with decreases in growth and survival traits, particularly in the Aleșd and Padeș trials, indicating a limiting effect of high-altitude conditions.
- Latitude of origin generally had a weaker and less consistent influence on the analysed traits compared to longitude and altitude.
- In the Padeș provenance trial, correlations with geographic gradients were generally weak, indicating a limited influence of geographic origin on the phenotypic expression of the analysed traits.
- Overall, the results suggest that longitude and altitude are the most ecologically relevant geographic gradients, although their effects depend on the test site and the trait analysed.

Transfer functions under the climatic conditions of the test sites

- Transfer functions highlight that provenance performance is significantly influenced by climatic differences between the place of origin and the test site.
- Transfer models for diameter at 1.30 m (DBH) were significant in all three trials, explaining between 12% and 19% of the variation.
- At Aleșd, DBH is negatively influenced by the mean temperature of the wettest quarter (BIO8) and positively by the standardised precipitation index over 3 months (SPI03), suggesting that higher temperatures during the wettest quarter may reduce diameter growth, while favourable precipitation early in the growing season supports it.
- At Făget, both predictors—the annual heat–moisture index (AHM) and the standardised precipitation index over 1 month (SPI01)—have negative effects, indicating that warmer and drier conditions, as well as short-term precipitation variability, may reduce diameter growth.

- At Padeș, the standardised precipitation index over 9 months (SPI09) has a positive effect, while isothermality (BIO3) has a negative effect, suggesting that long-term water availability promotes diameter growth, whereas higher thermal stability may limit it.
- Models for total height (HT) were significant in all trials, explaining between 10% and 23% of the variation.
- At Aleșd, both BIO8 and the standardised precipitation evapotranspiration index over 6 months (SPEI06) have negative effects, indicating that height growth is influenced by both temperature and water availability.
- At Făget, SPEI08 has a positive effect, while the frost-free period (BFFP) has a negative effect on height, suggesting that a favourable water balance over a longer growing period promotes height growth, whereas large variations in frost-free period may limit it.
- At Padeș, the annual heat–moisture index (AHM) positively influences HT, while isothermality (BIO3) has a negative effect, highlighting the importance of the heat–moisture balance.
- Transfer models for survival (SV) were significant in all trials, with the highest explanatory power observed at Aleșd.
- These models were univariate, each including a single significant climatic predictor.
- At Aleșd, the minimum temperature of the coldest month (BIO6) has a strong negative effect, indicating sensitivity to winter conditions.
- At Făget, precipitation of the wettest month (BIO13) negatively influences survival.
- At Padeș, precipitation of the coldest quarter (BIO19) has a negative effect, suggesting the influence of winter moisture conditions.
- Compared to DBH and HT, survival (SV) shows a clearer and stronger relationship with climatic variables.
- Across all three provenance trials, provenances from western North America—especially from Washington, but also from Oregon, Idaho, and southern British Columbia—are associated with favourable climatic differences, which partly explains their superior performance in DBH, HT, and SV and highlights good climatic matching.

Response functions under the climatic conditions of the test sites

- Response functions indicate that provenance performance is significantly influenced by the specific climatic conditions of the test sites.
- Models for diameter at 1.30 m (DBH) were significant in all three provenance trials, explaining between 9% and 12% of the variation.

- At Aleșd, DBH is positively influenced by the mean temperature of the driest quarter (BIO9) and negatively by the standardised precipitation evapotranspiration index over 3 months (SPEI03), indicating that summer temperatures favour diameter growth, while water availability at the beginning of the growing season may limit it.
- At Făget, DBH is influenced by SPEI02 and SPEI03, with nonlinear relationships, suggesting that diameter growth reaches optimal values under moderate moisture conditions.
- At Padeș, SPEI09 hurts DBH, and the model explains a relatively small proportion of variation, indicating a weaker climatic influence compared to Aleșd and Făget.
- Models for total height (HT) were significant in all provenance trials, explaining between 19% and 25% of the variation.
- At Aleșd, HT is positively influenced by the mean temperature of the wettest quarter (BIO8) and negatively by SPI03, indicating the importance of thermal regime and early-season water conditions.
- At Făget, HT is influenced by SPEI02 and SPEI08, with nonlinear relationships, suggesting that height reaches higher values under moderate climatic conditions, without thermal and hydric extremes.
- At Padeș, HT is influenced by the maximum temperature of the warmest month (BIO5), suggesting the existence of a thermal optimum beyond which excessive temperatures reduce growth.
- Response models for survival (SV) are multivariate at Aleșd and Făget and univariate at Padeș, including significant predictors.
- At Aleșd, BIO6 and SPEI06 have positive effects, indicating that milder winters and adequate water availability contribute to higher survival.
- At Făget, mean annual precipitation (BIO12) and SPEI05 positively influence survival, highlighting the role of water availability.
- At Padeș, the summer heat–moisture index (SHM) and mean annual precipitation (BIO12) positively influence survival, emphasising the importance of thermal and hydric balance.
- Compared to DBH and HT, survival (SV) shows the strongest relationship with climatic variables, especially in the Aleșd provenance trial.
- Across all three test sites (Aleșd, Făget, and Padeș), response functions indicate that provenances from western North America—especially Washington, as well as Oregon, Idaho, and southern British Columbia—show high performance, suggesting that their climate of origin favours the expression of growth potential.

5.2. Personal contributions

- Transfer and response functions were developed and applied for each test site, highlighting the different sensitivities of diameter at 1.30 m, total height, and survival to climatic variables of origin, as well as the complex nature of the climate–growth relationship.
- Multivariate selection of Douglas-fir provenances was applied using the MGIDI and MTSI indices, demonstrating their effectiveness in identifying high-performing and stable provenances.
- The results provide a scientific basis for the establishment of seed orchards classified as "tested" sources.
- Douglas-fir provenances with superior performance were identified, which can serve as base material for relaunching breeding programs and for producing forest reproductive material in Romania.
- The results contribute to supporting decision-making regarding the use of Douglas-fir under ecological conditions similar to those analyzed in western and south-western Romania.

5.3. Dissemination of results

A. Scientific papers published in Web of Science (ISI)-indexed journals

As first author:

Stoica, E.; Alexandru, A.M.; Mihai, G.; Scarlatescu, V.; Curtu, A.L. Evaluating Douglas Fir's Provenances in Romania Through Multi-Trait Selection. *Plants* 2025, 14, 1347. https://doi.org/10.3390/plants14091347

Stoica, E.; Alexandru, A. M.; Mihai, G.; Curtu, A. L. Variation in Survival and Stem Quality of Douglas-Fir Provenances: Insights from 47-Year-Old Common Garden Experiments in Romania. *Not Bot Horti Agrobo* 2025, 53, 14695. https://doi.org/10.15835/nbha53314695

As co-author:

Alexandru, A.-M.; Mihai, G.; **Stoica, E.**; Curtu, A.L. Multi-Trait Selection and Stability in Norway Spruce (*Picea abies*) Provenance Trials in Romania. *Forests* 2023, 14, 456. https://doi.org/10.3390/f14030456

Mihai, G.; Alexandru, A.M.; **Stoica, E.**; Birsan, M.V. Intraspecific Growth Response to Drought of *Abies alba* in the Southeastern Carpathians. *Forests* 2021, 12, 387. https://doi.org/10.3390/f12040387

B. Scientific papers published in journals indexed in international databases (BDI)

As first author:

Stoica E., Alexandru A.M., Mihai G., Curtu A.L., Douglas Fir Performance in Romania: Growth Insights from Common Garden Experiments, *Bulletin of the Transilvania University of Brasov.* Series II: Forestry, Wood Industry, Agricultural Food Engineering, Vol. 18(67) No. 2 – 2025. https://doi.org/10.31926/but.fwiafe.2025.18.67.2

C. Papers presented at national and international symposiums and conferences

Stoica, E.; Alexandru, A.M.; Mihai, G.; Scarlatescu, V.; Curtu, A.L. Analysis of Wind breakage of Douglas Fir (*Pseudotsuga menziesii* (Mirb.) Franco) Provenance Trials Established in Romania. 9th International Symposium Forest and Sustainable Development, 17-18 octombrie 2024, Brașov, România. Poster.

Stoica, E., Alexandru, A.M., Mihai, G., Assessment of genetic variability in Scot spine (*Pinus sylvestris* L.) provenance trials in Romania. 10th International Symposium Forest and Sustainable Development, 14-15 octombrie 2022, Brașov, România. Poster.

5.4. Future research directions

- Integration of additional variables (e.g., soil characteristics) to improve the explanatory power of climate–performance models.
- Detailed analysis of the impact of extreme climatic events (severe droughts, late or early frosts, heatwaves) on growth, wood quality, and adaptive traits of provenances, based on dendrochronological analyses.
- Extension of transfer and response functions by incorporating future climate scenarios to assess risks associated with climate change.
- Testing the applicability of MGIDI and MTSI indices in other experiments and for other tree species, to support multivariate selection in breeding programs.
- Development of recommendations for the use of Douglas-fir in western and south-western Romania.
- Analysis of age-to-age correlations to assess the potential for early selection.

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3. Alexandru, A.-M., Mihai, G., Stoica, E., & Curtu, A. L. (2023). Multi-trait selection and stability in Norway spruce (*Picea abies*) provenance trials in Romania. *Forests*, 14(3), 456. https://doi.org/10.3390/f14030456

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