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Using Adapted and Productive European Beech (*Fagus sylvatica* L.) Provenances as Future Solutions for Sustainable Forest Management in Romania

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Abstract: In the near future, it is predicted that the natural distribution range of forest tree species will be reshaped due to the rapid changes in climate conditions. The assisted migration of species in favorable environmental conditions, as future solutions for sustainable forest management, could be supported by genetic tests. This study aims to evaluate the adaptive potential of European beech (*Fagus sylvatica* L.) and the opportunities for applying assisted migration practices in the Carpathian region of Romania. Growth and stability performances, as well as phenotypic plasticity of 31 international beech provenances, were assessed in two common garden experiments located in optimum growing conditions and at the eastern margin of the beech distribution range, respectively. For all analyses, trees height, breast height diameter, and survival were determined. Survival and growth traits were higher by 6–8% in the ecological optimum for beech. The highest mean plasticity was obtained by three provenances from France and one from Denmark. Three provenances performed better in both trials. Increasing the management sustainability of beech forests in a changing climate might be possible by using assisted migration practices, which include the promotion of the highest adapted and productive provenances only in the provenance region where they performed.

Keywords: European beech; provenance trials; assisted migration; sustainable forest management; phenotypic plasticity; adaptive potential; growth and stability performances

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1. Introduction

The natural distribution range of forest tree species varies over time [1,2] and is influenced by climate, which is one of the principal drivers of species migration [3–7].

In the last decades, climate change and its negative effects on tree species have been intensely studied [8–13], and it was proved that one of the first steps in preventing negative impacts on forest ecosystems is to understand the adaptive capacity of tree species [14].

European beech (*Fagus sylvatica* L.) is one of the most common and important forest tree species in Europe's forestland [15–17]. In its extensive distribution, this species grows in different site conditions, from a lowland species in the northern part to a mountain species in the south [18]. The natural distribution limits are shaped by low temperatures on high-elevation sites and by the high temperatures and low amounts of precipitation in the low-elevation sites from the southern area [19,20]. It prefers fertile sites, and the atmospheric humidity can counterbalance the insufficient water from the soils [21]. In addition, it is a highly shade-tolerant species with a remarkable capability of competition [22] and natural regeneration, which may allow northward expansion [23,24]. It covers over 30% of the entire forestland in Romania and grows in various site conditions [25,26].

Recent studies report that in the center of its distribution range, beech appears to be affected by drought, which produced a growth decline in mature stands [12,27–29]. Growth reductions were also observed in other parts of the beech distribution range, such as Spain, Italy, and Hungary [30–32]. Kasper et al. [33] revealed that in the future, beech stands from the western part of Romania could face problems due to rising temperatures and could be replaced by oak species. Also, in the eastern part of Romania, beech stands were affected by the dry weather conditions, and the main limiting factor in this area seems to be the summer drought [34–36]. A recent study carried out in the Republic of Moldova shows that European beech stands from the eastern limit of the natural distribution range are very sensitive to water availability and extended drought events [37].

Taking into consideration the problems that beech faces nowadays regarding the sensitivity of seedlings to water stress [38,39], growth reduction in mature stands [8,11,12], increased mortality [40,41], the potential to recover after a drought period [42,43], and the adaptation potential of some provenances [44,45], this species is considered to be moderately drought-sensitive [14].

Due to the fact that the provenances test is considered to be very useful in testing the adaptability of tree species [46], many research projects were initiated in order to study the phenotypic variability and stability of beech in five series of international provenance trials installed across Europe [47,48]. In a provenance trial from Spain, bud burst started firstly in provenances from eastern and south-eastern Europe and also for provenances from lower altitudes [49]. Stojnić et al. [50] measured four provenance trials and observed that German provenances obtained lower values for height and a lower adaptive capacity to southern European environment conditions. Beech provenances from southeastern Europe showed faster growth, and bud bursts started earlier than other provenances, thus being inadvisable for introduction in this country because they were susceptible to late frost damage [51].

The adaptive capacity of tree species can be evaluated using phenotypic plasticity, which is the potential of a genotype to exhibit diverse phenotypes when it grows in different site conditions and also the capacity to withstand a changing climate [52–56]. High phenotypic plasticity was revealed for European beech in many studies. Stojnić et al. [44] reported high phenotypic plasticity of provenances for stomatal analysis; Müller et al. [45] found that German provenances had a plastic response for height increment and survival; and Vitasse et al. [57] pointed out the plasticity of beech regarding bud burst. Besides these, phenotypic plasticity is widely used in studies focused on modeling species' adaptive capacity in a changing climate [58–60].

In Romania, European beech is considered a resistant tree species. Because there were no clear reports of damages produced by drought, there is a general conception that beech is not a species in danger in terms of climate change. But if we consider that prevention is the key, not combating drought's negative effects that are predicted for the near future, there is a real need for research in the area of the adaptive potential and future distribution range of beech across Romanian Carpathians. Besides these, searching for potential adaptive and highly productive beech provenances, which is considered a starting point in the assisted migration process, is still a gap that needs to be filled by research studies.

Taking into account the current need to test and model the adaptive potential of tree species in different site conditions and to identify acclimated and adapted provenances, the main goal of this paper was to evaluate the adaptive potential of European beech in the environmental conditions of Romania along with the appraising of the opportunities for applying the assisted migration practices. To achieve this general objective, we focused on two international beech provenance trials and assessed (1) growth and stability performances and (2) phenotypic plasticity of provenances.

2. Materials and Methods

2.1. Common Garden Experiments and Tested Provenances

To test the adaptability of the European beech population, in 1986–1998, five series of international beech provenance trials were established across Europe. Forty-nine trials were installed in the last two series (1995 and 1998), which were the most representative series for the beech natural distribution range [47] (Figure 1). Besides these, in 2007, the international provenance trials network was extended in the Balkan region by installing seven trials with fifteen common provenances [61,62]. In 1998, twenty-six provenance trials were established in seventeen European countries. In the spring of 1998, two international provenance trials were installed in Romania at Alesd, Bihor country, and Fantanele, Bacau country [47,63]. In both trials, thirty-two provenances were planted, of which thirty-one are common for the two test sites (Table S1). Of these thirty-one provenances, thirty are European beech provenances, and one is a provenance of oriental beech (*Fagus orientalis*) originating from the south of Bulgaria [62].

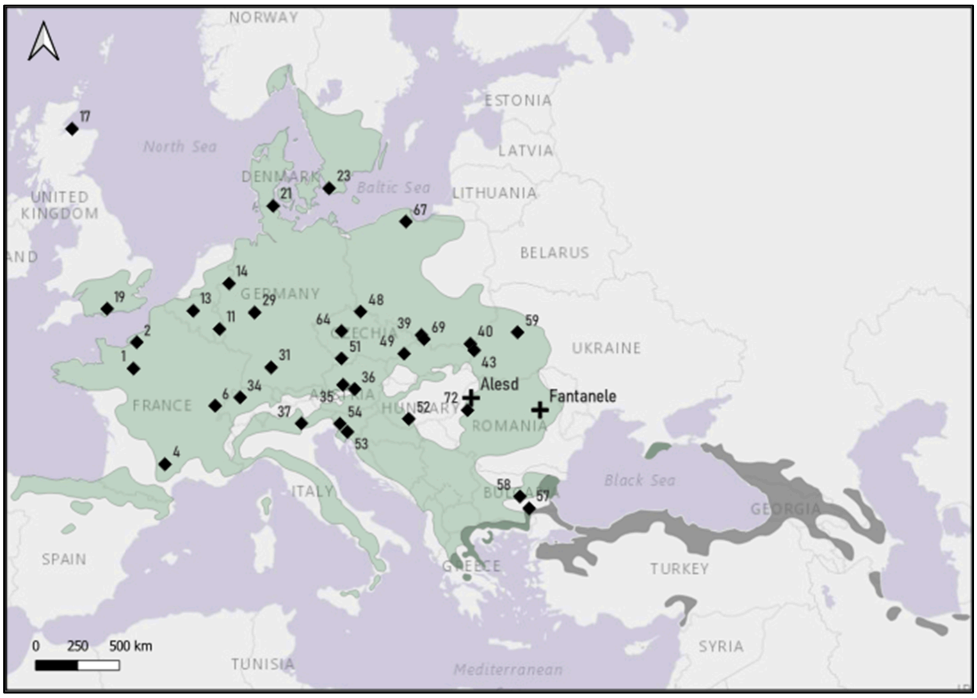

Figure 1. The natural distribution range of *Fagus sylvatica* (green) and *Fagus orientalis* (grey) [64], the locations of trials (black crosses), and provenances (black diamonds) [62].

A complete randomized block design with three replications and a total number of fifty seedlings per unitary plot was used. The planting scheme used had two meters of spacing between rows and one meter between seedlings. Each plot covers an area of one hundred square meters [47,48].

2.2. Measurements of Growth Traits and Site Conditions

In the spring of 2022, at the age of twenty-four years after planting, both trials (Alesd and Fantanele) were tested for growth and stability traits. The work methodology applied in each trial involved measuring five individuals, randomly selected using a preset scheme, from each provenance in each replication, thus summing a total number of fifteen measured trees per provenance in each trial. Trees' height (Th) and breast height diameter (Dbh) were measured for each selected tree, and for all provenances, the survival trees (S) were counted.

The Alesd test site is located in the Bihor Mountains at an elevation of 682 m. The slope has a 10° inclination and a southern exposition, and the soil is a typical eutricabosoil [65].

The Fantanele trial is located in the hilly area from the eastern part of the Carpathian Mountains, on a site with 276 m elevation, a slope characterized by an inclination of 6° with eastern exposition, and the soil is a typical luvisoil [66].

Regarding the climate condition at the testing sites (Figure 2), for the twenty-three growing seasons (1998–2021), the temperatures and the amount of precipitation were extracted using the Climate downscaling tool [67]. In addition, the temperature and air humidity were recorded for one year using data loggers installed in the two environments. The recorded climatic indicators were used to test the accuracy of data extracted from the above-mentioned climatic database.

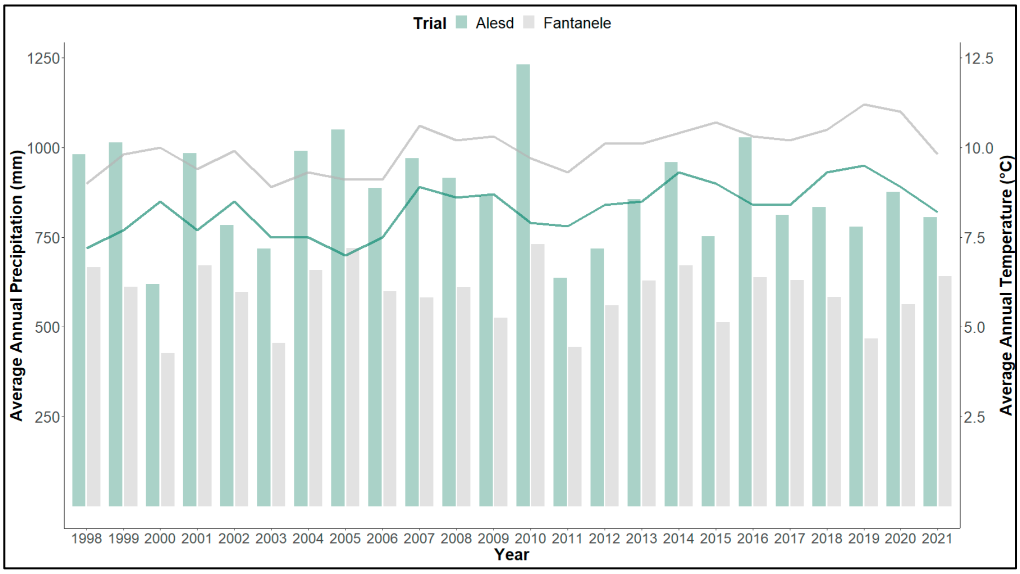

Figure 2. Climatic data for the period 1998–2021 (The bars represent the average annual precipitation amount, and the lines describe the average annual temperature for both environments).

The two testing environments clearly differ in terms of climate conditions for the analyzed period (1998–2021). In the Alesd trial, the annual mean precipitation was 877 mm, and the mean temperature was 8.3 °C. In the other trial (Fantanele), the mean temperature was 10.0 °C, and the mean precipitation was 591 mm.

Considering that in the two trials, a substantial number of provenances from Europe are tested together with a local population, and more than that, the site conditions are contrasting, it was a perfect fit for testing the performance and the adaptive capacity of beech in the Carpathian region of Romania.

2.3. Data Analyses

A linear model was applied to assess the differences between the common provenances and the two test sites. In the model, the provenance and the trial were the dependent variables, and the Th, Dbh, and S were used as independent variables. The precision of the model was tested using the residual plots. Besides these, the *t*-test was used to visualize the obtained differences in the graphics. Both analyses were computed in the R environment [68].

In the analyses of plasticity of provenances (PP), the Relative Distances Plasticity Index (RDPI) described by Valladares et al. [69] was used, and the calculation of this index was made using the R package Plasticity [70]. For a given trait, the RDPI was calculated as the absolute value of the difference between two individuals of the provenance that grows in different site conditions, divided by the sum of the two individuals and all together divided by the entire number of distances. The output values of RDPI can vary between zero (which means no plasticity) and one (which describes height plasticity) [69]. In the present study, the beech provenances tested in the two environments (Fantanele and Alesd) were included in the calculation of the RDPI using the measured traits (Th, Dbh, and S). For Th and Dbh, the values of sampled trees from each provenance and replication were used as input variables, and for S, the percentage of living trees from each replication was used.

A graphical method was used to point out the best-performing provenances based on the mean values recorded by provenances in terms of S and Th. This analysis was applied in the case of each experiment, and the provenances that registered values above the trial mean for the selected traits were included in the rank of the provenances with high performance. The S was used to assess the stability and Th for the growth performance of provenances. The Th was used instead of Dbh because no significant differences between provenances were reported for this trait; thus, without variability, the performance of provenances could not have been separated.

The graphics and data manipulation used in this paper were computed using the R packages ggplot2, version 3.4.2 [71] and dplyr, version 1.1.2 [72]. The distribution map of provenances and trials was made using the Qgis software, version 3.32.0-1 [73].

3. Results

Significant differences were obtained between testing sites for all analyzed traits (Table 1). However, the differences between provenances were significant only for S in both trials and for Th in the Alesd trial. In the case of Dbh, no significant differences were reported between provenances in both test sites.

Table 1. The interactions between provenances and test sites.

Interactions	Site	S	Th	Dbh
Between provenances	Alesd	0.000 ***	0.000 ***	0.360
	Fantanele	0.006 ***	0.052	0.604
Between test sites		0.000 ***	0.000 ***	0.000 ***

*** The black stars represent the level of significance.

3.1. Stability Performances

The differences in S between common provenances and test sites were used to assess the stability in the two environments and to highlight the highest and the lowest stability. Significant differences were reported between the two test sites in terms of S (8%), but provenances manifested different behaviors regarding stability. The highest mean value for S was recorded by provenance 58 (Maglij, Bulgaria) in the Alesd trial, and the lowest S was recorded in the same trial by provenance 14 (Aranikm, The Netherlands). High variations of this trait were observed at provenance 1 (Perche, France) and 29 (Dillenburg, Germany), which recorded values for S 30% higher in the Alesd trial, where the site conditions are more favorable for beech growth. Even if the majority of provenances obtained higher values for S in the Alesd trial, the provenances 36 (Eisenerez, Austria), 13 (Soignes, Belgium), and 14 (Aranik, The Netherlands) obtained slightly higher values for S in the limiting site conditions of the Fantanele trial, but the differences were statistically insignificant. Besides these, there were provenances that obtained high S in both trials, while others registered low S in both environments, thus revealing the different responses of provenances to the interaction with environment conditions of Romania. The Romanian provenance 72 (Bihor, Izbuc), which originates from the same provenance region as the Alesd trial, recorded similar and over 50% values for S in both trials, thus having a good stability level in the two environments. The Oriental beech provenances (57 Gramaticovo, Bulgaria) obtained similar low results in the two trials, and the low values of S indicate lower stability of this variety in the environmental conditions of the testing sites (Figure 3).

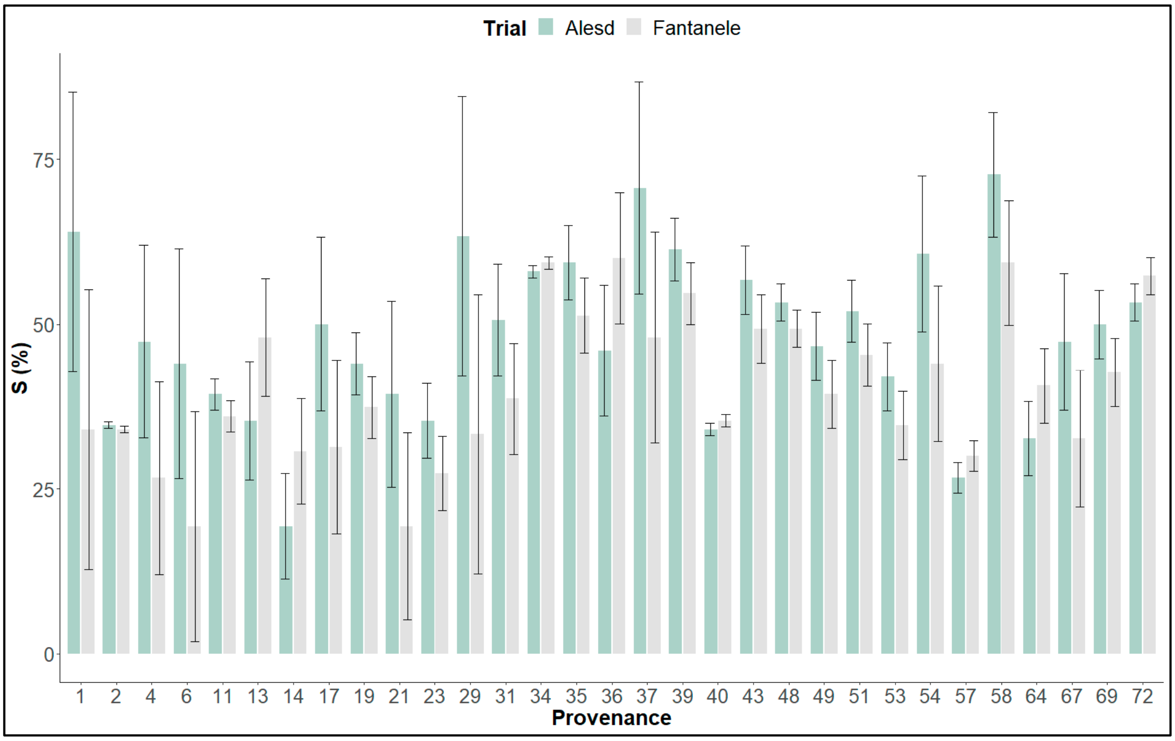

Figure 3. The survival of the 31 beech provenances in the two testing sites (The black lines represent the error bars).

3.2. Growth Performances

The analysis of growth traits revealed significant differences between provenances and testing sites, with a difference between sites that reached 8% for Th and 6% for Dbh, both in favor of the Alesd site, which means that the trial site conditions had an evident influence on the Th and Dbh increment. For 13 of the provenances, significant ($p < 0.05$) to highly significant ($p < 0.001$) differences between testing sites were registered for Th, while for Dbh, only two provenances recorded significant and distinctly significant ($p < 0.01$) differences between test sites. Interesting behavior was observed at provenance 40 (Poland), which recorded higher values for growth traits in the limiting conditions of the Fantanele trial.

Regarding Th, the highest mean value was recorded in the Alesd trial by provenance 1, which originates from the west of France, and the lowest mean value was obtained in the Fantanele trial also by a France provenance (4) from the south of the country. Only provenances 23 (Torup, Sweden) and 40 (Tarnawa, Poland) obtained higher values for Th in the Fantanele trial; all other provenances recorded higher Th values in the Alesd trial.

Relating to Dbh, there were two provenances from Great Britain (17) and Poland (43), which obtained significantly higher values for this trait in the Alesd trial. The highest mean value for Dbh was obtained by provenance 43 (Jawornik, Poland) in the Alesd trial, and the lowest value was recorded by provenance 53 (Postojna Masun, Slovenia) also in this test site (Figure 4).

In the case of the Romanian provenance 72 (Bihor-Izbuc), it was observed that the transfer to a warmer and drier site condition (from the Fantanele trial) significantly decreased the height growth, but the Dbh was not influenced (Figure 4). The oriental beech provenance (57 Bulgaria) showed a higher Dbh in the Alesd trial but almost the same mean value for Th in both site conditions, so the transfer to a wetter and colder environment does not seem to increase the height growth. Even if not for all provenances, the differences between test sites were significant; it is clear that in the Alesd trial, the conditions for beech growing are more favorable than in the other trial.

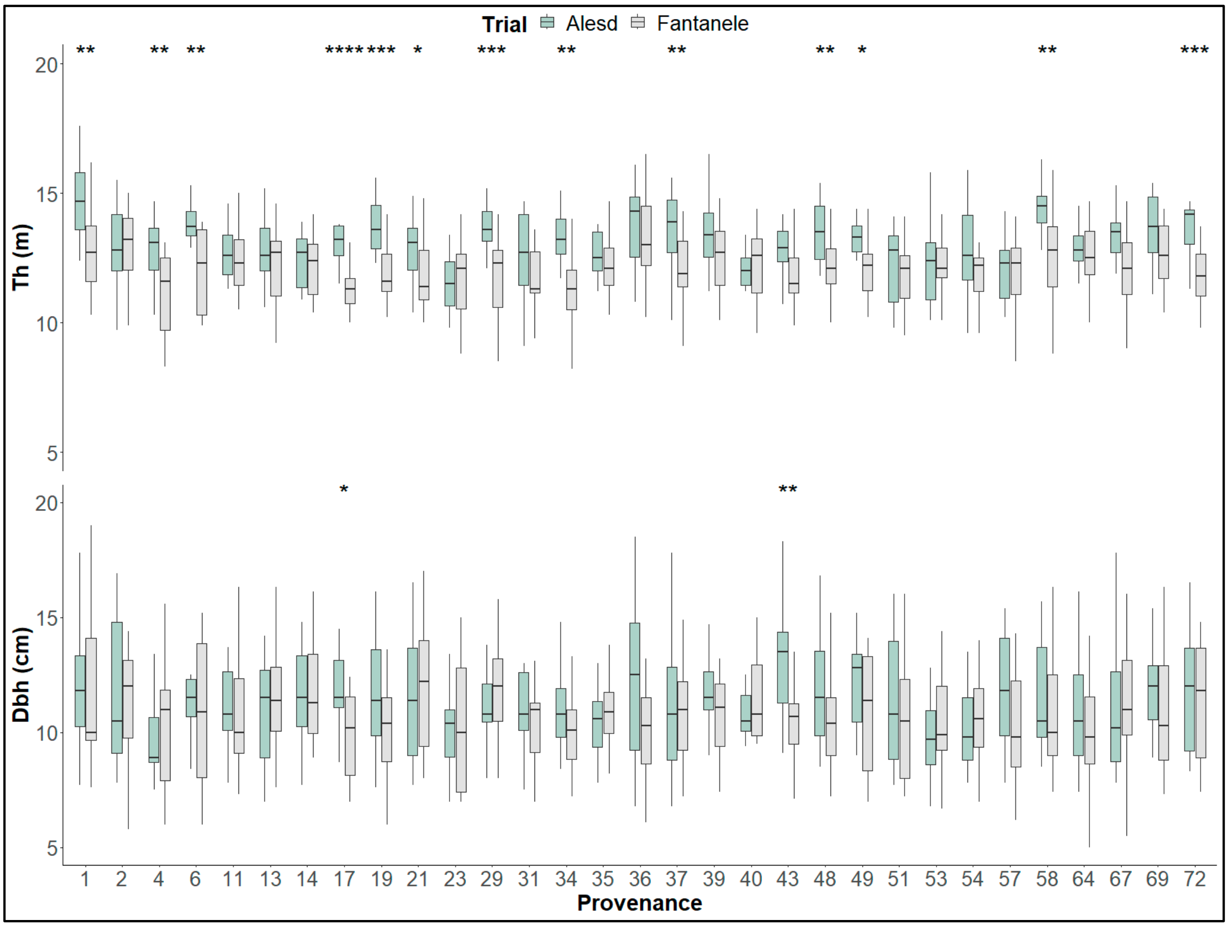

Figure 4. The growth traits of the 31 common provenances installed in the two test sites (The boxplot describes the minimum value, the first quartile, the median, the third quartile, and the maximum value. The *, **, *** and **** above the boxplots represent the level of significance revealed by the *t*-test computed between the two test sites).

3.3. Provenances Adaptability (Phenotypic Plasticity)

The PP was evaluated using the RDPI and computed for all the traits used in this study (Th, Dbh, and S).

In general, the values obtained by provenances for plasticity were low, especially for Th and Dbh, but there were differences between provenances, revealed by the Tukey test. The highest plasticity value was registered by provenance 34 (Switzerland) for height and by provenance 36 (Austria) for diameter. In the case of S, the plasticity values were higher than for the growth traits, and the provenances 6 (France) and 21 (Denmark) obtained the most increased PP. In contrast, the lowest values for PP were recorded by provenances: 35 (Austria) for Th, 40 (Poland) for Dbh, and 43 (Poland) for S (Figure 5).

The mean of plasticity for all analyzed traits revealed that three provenances from France (1, 4, 6) and one from Denmark (21) registered the highest level of PP. At the opposite pole, two provenances from Poland (39, 43) and one from Slovenia (53) achieved the lowest PP.

3.4. Best-Performing Provenances

The provenances that obtained values for S and Th over the trial mean were selected as being the best-performing in the environmental condition of the two trials.

In the case of the Alesd trial, from all selected provenances (green circles in Figure 6), the highest performances were obtained by 1 (France), 52 (Hungary), and 58 (Bulgaria). The local provenance 72 (Bihor-Izbuc) was also included in the rank of the best-performing provenances. On the opposite pole, the lowest performance was observed at provenances 23 (Sweden), 14 (The Netherlands), and 57 (Oriental beech), which originates from low-elevation sites.

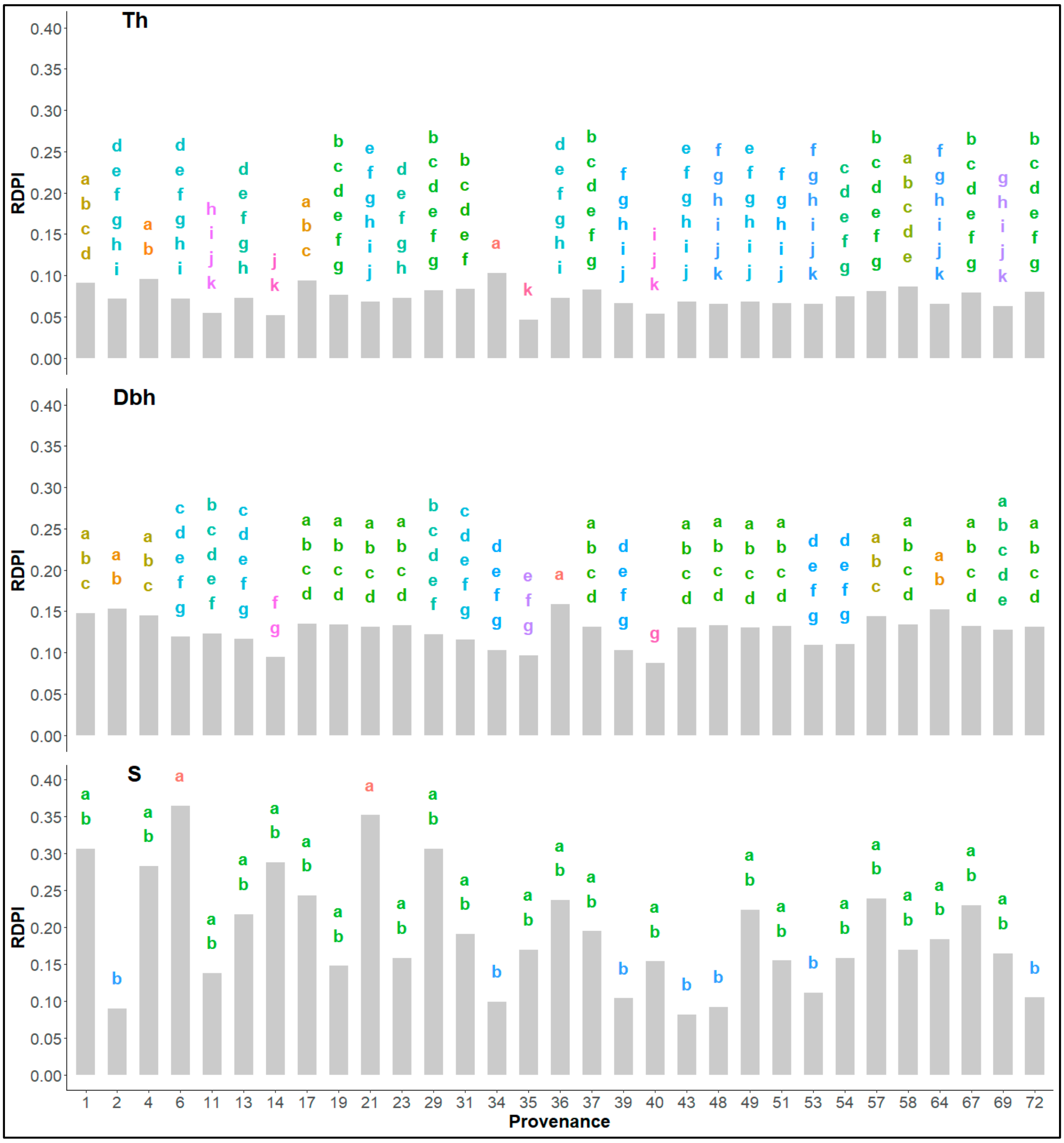

Figure 5. RDPI computed for all analyzed traits. (The letters above bars represent the groups revealed by the Tukey test).

In the Fantanele trial, the best provenances were 36 (Austria), 58 (Bulgaria), and 39 (Poland), while the lowest performance was observed at provenances 4 (France), 17 (Great Britain), and 21 (Denmark). Even if the site climatic conditions are not favorable for beech, these provenances had a good reaction in this experiment, being thus able to grow in challenging site conditions.

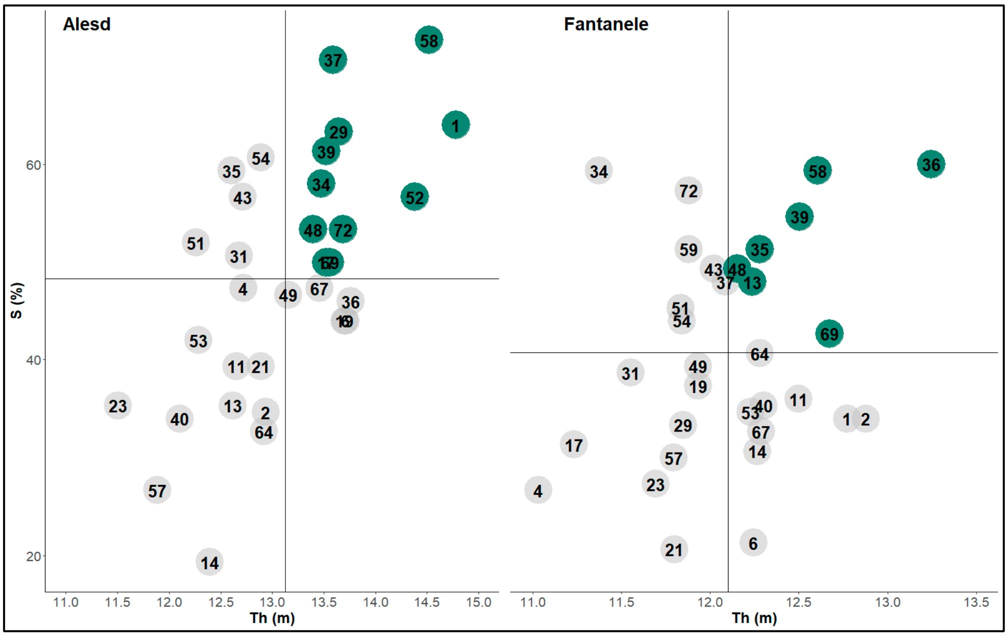

Figure 6. The best-performing provenances in the two trials (The numbers represent all the tested provenances, green circles mark the best-performing provenances, and the black lines represent the trial mean for Th and S).

Contrary performance in the two environments was observed at provenances 29 (Germany) and 17 (Great Britain), which were included in the rank of best-performing provenances in the case of the Alesd trial, but in the Fantanele trial obtained a low performance. However, the provenance from Belgium (13) was one of the best-performing in the Fantanele trial and reached a lower performance in the Alesd trial (Figure 6).

The mean performance of the common provenances in both trials indicated that the best-performing provenances were 1 (France), 58 (Bulgaria), and 36 (Austria), which registered a high performance in both trials, even higher than the Romanian provenance (72). The interesting fact is that the France provenance (1) came from a low-elevation site (205 m) and recorded a high and similar performance to the Austrian and Bulgarian provenances (36 and 58), which were transferred from high-elevation sites (1100 m). On the other hand, the low-performing provenances in both trials were 14 (The Netherlands), 23 (Sweden), and 57 (oriental beech), all transferred from low-elevation sites.

The good performance of the Romanian provenance over the two test sites is a sign of the stability of this population, which is adapted to the conditions of the Romanian Carpathians. In this case, the beech population from Bihor-Izbuc might be useful to be conserved as a forest genetic resource. However, the reduction in the height increment, when the provenance was transferred from a high to a low elevation raises the problem of moving the forest reproductive material, which must be conducted only in adjacent provenance regions. Besides these, forest managers who are interested in increasing the productivity and stability of beech forests might consider the assisted transfer of best-performing provenances in the regions where they reached the highest performance.

4. Discussion

4.1. Growth and Stability Performance

The growth performance and the survival of provenances can be considered proof of the adaptive potential of species in certain environmental conditions. Thus, the provenance tests are one of the most important sources of information regarding the adaptive potential and the phenotypic plasticity of different tree populations [74].

The international beech provenances revealed a good level of adaptation in the Romanian test sites, with a specific response influenced mainly by the site conditions and by the genetic variation. The environmental conditions of the trials significantly influenced the stability of the tested provenances and confirmed the fact that in favorable conditions, beech provenances manifest higher stability, as was reported by other studies that were focused on international beech provenance trials [75,76].

The high survival rate of European beech provenance from Bulgaria (58) was associated with a high level of stability in both trials. In contrast, the provenance from the Netherlands (14) obtained one of the lowest stability performances in Romanian trials. This result has also been reported by other studies that highlighted the low survival rate of the provenance fourteen in two trials from Ireland and The Netherlands [51,77]. At the bottom of the ranking, regarding stability, was also the oriental beech provenance (57), which indicates a poor adaptation to the Romanian site conditions. The low adaptive potential of the oriental beech to the natural distribution range of the European beech was also mentioned by von Wuehlisch et al. [75], based on the low performance obtained by a Turkish provenance in several trials established in Europe. This maladaptation behavior may be caused by the cold period from the winter and the shorter growing season, which can be the limiting factors for this variety of beech.

Many studies reported high variation between sites and provenances for growth traits in the international beech trials [50,75,76,78,79]. The same trend was observed in the Romanian test sites, especially for Th, as was pointed out also by Krajnc et al. [80]. A comparison study between German and Bulgarian beech provenances [81] highlighted the superiority of Bulgarian provenances in terms of height growth. Similar results were obtained in the present study in the case of the Bulgarian provenance (58), which recorded one of the highest values for Th in both Romanian environments. However, when the Bulgarian provenances were transferred to the German trials, the performance in the case of height increment was lower in comparison to local provenances [82].

The European beech populations from the Balkans are genetically different from those of Central Europe because they seem to have migrated from different glacial refuges [83]. Taking into consideration this post-glacial migration pattern, the future forecasts that predict shifts in the southern natural distribution range to the north [84,85], and the lower level of performance recorded by the Bulgarian provenance in Central Europe conditions [82] in contrast to the high adaptive capacity of the Bulgarian beech provenance to the environmental conditions of Romania testing sites, indicate that in the future it will be possible for European beech populations from Bulgaria to find more suitable conditions for growth in the Carpathian region of Romania and to migrate to these areas.

The Romanian provenance (72) reached a high performance across the two different sites for growth and stability traits, thus confirming the adaptation to local environmental conditions. Despite that, the transfer to the limiting site conditions from the eastern edge of the distribution range of beech significantly decreased the Th increment, but the Dbh and the S were not influenced. The performance of this provenance was also evidenced in previous studies that tested adaptability at juvenile age in the Romanian trials [86], and also in one trial installed in Ireland [51]. However, several studies showed the low performance of the Romanian provenances tested in Serbia, Croatia, and Bosnia and Herzegovina [50,87,88], and the low genetic variation of the provenance 72 (Bihor-Izbuc) [89].

From the perspective of environmental changes, many authors have tried to find resilient beech populations, which can withstand restricted growing conditions [90–94]. Referring to the present study, the provenances that exhibit slightly higher adaptations to the limiting conditions from the Fantanele trial were 36 (Austria), 39 (Poland), and 58 (Bulgaria). Moreover, the Belgian provenance (13) manifested a better adaptation in the Fantanele trial than in the optimal conditions from the other test site. Thus, these beech populations might better cope with difficult growing conditions.

After analyzing the two series of international beech provenance trials, Wuehlisch et al. [75] confirmed the existence of a high genotype by site interaction and an adaptive potential of some provenances to different environments. This aspect was validated by other studies [44,80,82] and by the results obtained in the present survey, because of the distinct reactions of provenances to the contrasting conditions of the two test sites.

4.2. Provenances Adaptability (Phenotypic Plasticity)

One of the most important benefits of phenotypic plasticity is the stimulation of the adaptive process of a population to different environments, compared to natural selection which is a slow process that leads to adaptation [55].

In general, beech plasticity can be related to the variations, in specific traits, among distinct environments [45,95,96] or can be quantified using plasticity indices [97,98] as was the case in this study. All studied traits differed significantly between the two test sites, and the majority of provenances obtained higher values in the Alesd site conditions, which is placed in the natural distribution range of European beech. The RDPI results revealed lower phenotypic plasticity for the growth traits compared with survival plasticity, thus indicating that provenances manifested a plastic response, especially for S, to the transfer from optimal conditions to limiting ones. These results might argue that beech provenances can survive in different environments, but productivity will decrease in case of limiting conditions. In line with these findings, Stojnik et al. [44] pointed out that the high plasticity of the leaf's anatomical traits led to the physiological adaptation of beech provenances to severe environmental conditions, while Frank et al. [98] concluded that the phenotypic plasticity of beech seedlings, in the case of the growth traits, allows this species to cope with environmental changes. The difference between using a simple plasticity index, as was the case of the abovementioned studies, and our study, where we use RDPI, is related to statistical significance. The RDPI is considered to be more complex in computing but also more statistically powerful, so it is more appropriate to use this approach in the analysis of the plasticity difference between genotypes [69]. Differences between provenances regarding the mean plasticity for all traits showed that three provenances from France (1, 4, 6) and one from Denmark (21) recorded the highest PP and seemed to have a better capacity to adapt to different environmental conditions.

4.3. Implications for Assisted Migration and Forest Management

The assisted migration is known as a technique that implies human intervention in assisting the transfer of populations or species from the native environment, where there are threats of extinction due to the changes in the climate conditions, to new areas where the site conditions can support the growing process of trees [99]. The importance of this technique in the direction of forest management is related to maintaining the stability and productivity of stands [100], using reproductive material that is adapted to climate conditions and ensuring thus the productivity of stands up to the rotation period [101], along with preserving the ecosystemic services provided by forest [102]. However, these important features cannot be achieved without testing the adaptive and productive capacity of tree populations, and the only way to accomplish that is by changing the species environment using genetic tests [103,104].

The present survey brings new information in the direction of the assisted migration topic. By testing the adaptability and performance of several beech provenances in contrasting environments from the Romanian Carpathians, useful insights into the increasing productivity and stability of beech stands from this region were provided, as well as recommendations for the reforestation process.

The valuable provenances of European beech, which confirmed the adaptation and acclimation to Romanian test sites and also the potential to adapt to stressful conditions, will be an important source of reproductive material conservated ex-situ, available for use by state forest administrators and by the private forest stakeholders in the assisted migration process.

4.4. Study Limitations and Future Perspectives

The variability between provenances was tested only at the phenotypic scale. A complete differentiation between provenances could be conducted by genetic structure analyses with microsatellites, and the provenances that grew well in the limiting conditions from the Fantanele trial might be tested with genetic markers for particularities of adaptation. These genetic analyses of provenances will be considered in another study. Also, phenology is a very important key in studying the adaptive capacity of forest tree species, which needs to be conducted in these trials in order to complete the results about the adaptation potential because provenances that manifest high performance may be predisposed to damages produced by frosts.

Moreover, in the direction of the assisted migration modeling topic, future analyses based on the international beech provenance trials will provide a more realistic perspective regarding the suitability of site conditions from the Romanian Carpathians area for assisted transfer of beech provenances.

5. Conclusions

Twenty-four years after planting, the international beech provenances showed adaptations and acclimation to the testing sites in the Romanian Carpathians, but the less favorable growing conditions of the eastern limit of the distribution range of beech significantly narrowed their performance.

The phenotypic plasticity, together with the good level of performance recorded by international beech provenances, suggest that European beech possesses the adaptive potential that allows this species to cope with the predicted changes in the climatic conditions and to colonize different environments. The analysis of plasticity revealed that three provenances from France (1, 4, 6) and one from Denmark (21) recorded the highest level of mean plasticity and appeared to have a better capacity to adapt to different environmental conditions.

The best-performing provenances, which recorded an even higher performance than the local population in both trials, might be suitable for assisted transfer in the Carpathian forests, in the interest of increasing productivity and stability of beech stands. However, considering the significant differences between testing sites and the contrary reaction of some provenances, it is recommended to use the best-performing provenances only in the provenance region where they reached the highest performance.

Conserving the valuable beech populations as a method of increasing the sustainability of forest management in a changing climate might be an appropriate way to maintain the genetic diversity of forests and to provide tested reproductive material that can be used in the practice of the assisted migration process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13020183/s1, Table S1: Trials and tested provenances.

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